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THE EFFECTS OF WATER CONTENT ON THE UNIAXIAL MECHANICAL PROPERTIES OF WN1 CORE SAMPLES

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1. INTRODUCTION

The effect of moisture content on the uniaxial mechanical properties of rock specimens has been the subject of considerable study. It is well documented that water content influences such properties as modulus of elasticity, uniaxial compressive strength, compressional wave velocity and Poisson's ratio. The degree of that influence, however, varies considerably with rock type, texture, density, porosity, anisotropy, stress and temperature (1). Rock characterization conducted as part of the Nuclear Fuel Waste Management Program (NFWMP) at CANMET generally utilizes surface air dried specimens for uniaxial compression testing. The question arises, therefore, as to what extent the initial specimen conditioning affects the laboratory scale mechanical properties determined for samples tested as part of the NFWMP.

To provide some answers, 31 samples were selected from borehole WN1 located in the Lac du Bonnet batholith near Pinawa, Manitoba. Petrographic information as well as previous test programs indicate that the rock, from approximately 20 m to 450 m, is very uniform, both in terms of composition and mechanical behaviour (2,3,4). The samples, ranging in depth from 70.66 m to 336.09 m, were divided into three groups; oven dried, surface air dried, and saturated, according to their condition just prior to testing. The specimens were subsequently subjected to compressional wave velocity (P-wave) and uniaxial compressive strength measurements.

The purpose of this report is to briefly outline the test procedures, present the experimental data and note any changes in the mechanical properties which may occur as a result of the varying specimen water content.

2. GEOLOGICAL DESCRIPTION OF ROCK SPECIMENS

Thirty one specimens were prepared from borehole WN1 ranging in depth from 70.66 m to 336.09 m. No visible fractures were present in the core.

The granitic specimens were generally homogeneous, pinkish and massive, showing mineral compositions in the following approximate proportions: 45 to 60% potash feldspar; 20 to 25% plagioclase feldspar; 25 to 30% quartz and 5 to 10% biotite and other accessory minerals. Samples used for testing had an approximate porosity of 0.3% (5).

More complete analyses may be found by Chernis (2) and Wong (3).

3. DESCRIPTION OF TEST MEASUREMENTS

Cylindrical test specimens with an average length to diameter ratio of about 2.4 were used for these measurements. Samples were cut to slightly over their final dimensions using a diamond saw and water as a coolant. Samples were ground to their final dimensions and tolerance (length variation +/-0.001* specimen diameter, perpendicularity +/-0.25 deg., flatness +/-0.025 mm) using the double lapper developed at CANMET (6).

To carry out elastic deformation measurements, strain gauges oriented to measure axial and transverse strain were cemented to specimen surfaces prior to the initial conditioning. All four strain gauges were centered equidistant from the two ends of the specimens with gauges of similar orientation located on opposite sides of the specimen. The axial and transverse gauges were connected in series to form single active gauges which were then used in half bridge configurations for strain measurement.

Dried specimens were heated under vacuum at a rate of 0.35°C/min. to 63°C. These were left in the oven overnight and then stored in a dessicator until immediately before testing.

Strain gauges applied to specimens which were to be saturated were covered with two protective coatings* and completely immersed in water for at least seven days prior to testing.

The final specimen dimensions including density and their initial conditioning are contained in Table 1.

3.1 COMPRESSIONAL WAVE VELOCITY MEASUREMENTS

3.1.1 A) Equipment and Measurement Procedures

Terrametrics sonic velocity equipment was used to conduct p-wave tests. This consisted of a sonic pulse generator (maximum amplitude of 800 volts), pulsing and sensing heads (resonant frequency of 600 KHz) and a Tektronix Type 555 Dual Beam Oscilloscope equipped with delay sweep. A repetition rate of approximately 60 pulses per second was used.

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*BLH Barrier 'B'.

The pulsing head, excited by the generator, was used to send stress waves into the specimen which were detected by the sensing head. The sweep of the oscilloscope, which was triggered by the onset of each generated pulse, was used to measure the arrival time of the compressional wave.

Prior to testing, a zero delay time was calculated to account for travel time required to traverse the pulsing and sensing heads themselves. This was accomplished by measuring the time required to travel across steel specimens of different lengths. These travel times were then extrapolated to a steel specimen of zero length thereby yielding the zero correction.

3.1.2 B) Data Treatment

Using the time of transit, t_p, the zero delay of the system, t_o, and the specimen length, L, the compressional wave velocity, V_p, of the sample was determined according to the equation:

$$V_p = \frac{L}{t_p - t_o} \tag{1}$$

Combining the V_p velocity of a specimen, with the Poisson's ratio determined by strain gauge measurement, the dynamic Young's modulus of each specimen was determined using the following formula:

$$Ed = Vp^2 \rho(1+\mu)(1-2\mu)/(1-\mu) \tag{2}$$

where Ed = dynamic Young's modulus

ρ = specimen mass density

μ = Poisson's ratio

3.2 UNIAXIAL COMPRESSION TEST

3.2.1 A) Equipment and Measurement Procedures

Measuring and recording equipment included two Bruel and Kjaer Type 1526 strain indicators which supplied voltage analog outputs of axial and transverse strain to a Fluke 2280A data logger. Data blocks of load and corresponding strains were recorded at three second intervals throughout the tests. These data were transferred to a VAX 11/750 where these were reduced and transformed into plots of stress versus strain. The failure load was used to determine the uniaxial compressive strength of the specimen.

3.2.2 B) Data Treatment

Stress/strain curves were generated according to the transformed output utilizing a cubic spline fit. Young's modulus was determined using the first derivative of the appropriate interval of the fit at 50% of the failure load. The ratio of the tangent to the transverse strain curve to the tangent to the axial strain curve at the 50% failure point was used to determine the specimen's Poisson's ratio. The ultimate compressive strength of each specimen was calculated by dividing the specimen failure load by specimen cross sectional area.

4. DATA SUMMARY

Summaries of the uniaxial mechanical properties of the oven dried, surface air dried, and saturated samples are contained in Tables 2, 3 and 4 respectively. The mean mechanical properties for each test group are given in Table 5. Figures 1 through 31 represent the computer generated stress/strain curves obtained from the uniaxial compression tests.

The mean zero pressure velocity determined for samples prior to conditioning was 4.79 km/sec (σ = 0.17). This can be compared to values of 4.69 km/sec (σ = 0.16) for oven dried specimens and 5.96 km/sec (σ = 0.12) for saturated specimens. These resulted in mean dynamic moduli values of 58.06, 61.78 and 121.79 GPa for the oven dried, air surface dried and saturated specimens respectively.

Both the oven dried and saturated specimen groups exhibited mean uniaxial compressive strength of 198 MPa (with standard deviations of 14 and 18 respectively). Surface air dried results showed a mean uniaxial compressive strength of 200 MPa (σ = 12).

The tangent moduli of elasticity apparently increased with increasing water content with the oven dried, surface air dried and saturated groups having mean values of 66.81, 69.29 and 71.24 GPa respectively.

5. DISCUSSION

5.1 COMPRESSIVE WAVE VELOCITY AND DYNAMIC MODULUS

The velocity of a compressional wave through a rock specimen is dependent on the combined elasticity of the mineral skeleton and the pore filling material (1). Water, present as an infilling material, offers an acoustic

medium of transfer five times faster than air. Consequently, as the water content increases, the total velocity of the rock sample increases (if additional water causes no weakening of the matrix).

Wyllie et al. (7) and Broch (8) noted that, especially in high velocity rocks, the bulk of the velocity increase associated with increasing water content occurs as the water content increases from 70% to fully saturated. Similar behaviour is indicated in the present study where the velocity increased by only 2% as the samples went from an oven dried state to approximately 20% saturated. Tests conducted on fully saturated samples, however, showed a mean increase of 27% in velocity above the dry state.

The increase in compressional wave velocity also results in the dramatic rise in dynamic modulus with increasing water content. The mean dynamic modulus determined for saturated specimens was approximately 110% higher than that of the oven dried group.

5.2 UNIAXIAL COMPRESSIVE STRENGTH

Increasing moisture content generally results in a decrease in the compressive strength of rock although the effect varys considerably with rock type. Obert, Windes and Duvall (9) when working with granites, observed an average increase in compressive strength of 6% for oven dried rocks and a decrease of 12% for those in a saturated state. Colback and Wiid (1965), however, reported strength differences on the order of 50% when studying quartzitic shale and quartzitic sandstone.

For all intents and purposes, the WN1 core samples studies here exhibited little, if any, effects on the compressive strength with changes in the moisture content (varying by only 1 MPa over the three ranges of conditioning).

5.3 MODULUS OF ELASTICITY

The mean modulus of elasticity was seen to increase with increasing moisture content. Surface air dried specimens exhibited an average increase in modulus of 4% over oven dried samples while the average modulus determined for saturated specimens was approximately 7% higher. This agrees well with previous work done by Obert, Windes and Duval (9).

It seems logical to assume that increasing water content is lending some support to micro-cracks and pores which might otherwise collapse if these

were simply air filled. Again, this type of behaviour will only occur if the addition of water causes no weakening of the rock matrix.

6. SUMMARY AND CONCLUSIONS

Results indicate that varying water content has little or no effect on the uniaxial compressive strength of the rock type studied here. Also, although an increasing trend in elastic modulus with increasing water content is apparent, it is not pronounced. The amount of extra work required in sample preparation to control the moisture content, therefore, seems unwarranted.

Velocity measurements and consequently dynamic modulus estimates are, however, profoundly affected by the water content. Rock, in situ, is almost certainly saturated and if laboratory measurements are being conducted to reflect this condition, then these too, should be conducted under saturated conditions. Broch (8) noted that samples of quartz diorite, amphibolite and gneiss exhibited a 25% drop in water content when saturated samples were exposed to air for only ten minutes. One will, therefore, appreciate the need for great care in sample preparation if a good estimate of the saturated compressional wave velocity is required. Having said this, it is interesting to note that the best correlation between the dynamic modulus and the tangent modulus of elasticity occurs when measurements were taken using partially saturated specimens (approx. 20% water content).

It has been postulated by several authors that the uniaxial compressive strength of a rock is a function of its surface-free energy (8,10). Since the surface-free energy is directly related to the surface tension of the liquid the rock is immersed in, it is important that subsequent studies along this line, include uniaxial testing of specimens which are completely immersed in water.

Due to the variability of the effect of water content on the mechanical properties of different rock types it would probably be of benefit to conduct similar studies of this type on other research areas within the NFWMP.

7. ACKNOWLEDGEMENTS

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Table 1 - Specimen dimensions, density and test conditions of WN1 core

Specimen identification	Length (mm)	Diameter (mm)	Density (gm/cc)	Conditioning
WN1-74.03	107.67	44.72	2.63	Air dried
WN1-74.14	105.40	44.74	2.62	Saturated
WN1-74.25	108.76	44.74	2.54	Air dried
WN1-74.36	108.11	44.77	2.61	Oven dried
WN1-74.54	107.64	44.74	2.63	Saturated
WN1-74.65	104.23	44.72	2.63	Saturated
WN1-74.76	107.53	44.76	2.63	Air dried
WN1-75.05	105.01	44.76	2.62	Air dried
WN1-75.16	104.40	44.76	2.63	Saturated
WN1-75.27	108.39	44.76	2.63	Air dried
WN1-76.03	108.66	44.76	2.63	Air dried
WN1-76.25	103.33	44.78	2.62	Air dried
WN1-76.36	107.97	44.81	2.61	Oven dried
WN1-76.63	108.60	44.78	2.62	Air dried
WN1-76.74	104.13	44.78	2.62	Air dried
WN1-76.85	105.48	44.79	2.62	Saturated
WN1-77.30	107.05	44.78	2.63	Oven dried
WN1-78.00	108.89	44.78	2.63	Air dried
WN1-78.11	103.21	44.78	2.64	Air dried
WN1-78.22	109.01	44.77	2.63	Saturated
WN1-78.36	105.34	44.79	2.62	Saturated
WN1-78.47	105.27	44.79	2.62	Saturated
WN1-78.60	108.49	44.79	2.62	Oven dried
WN1-79.30	103.23	44.74	2.62	Saturated
WN1-79.41	103.21	44.78	2.62	Air dried
WN1-79.52	103.41	44.68	2.62	Saturated
WN1-335.54	108.29	45.02	2.62	Oven dried
WN1-335.76	107.99	45.02	2.62	Oven dried
WN1-335.87	107.98	45.05	2.62	Oven dried
WN1-335.98	108.56	45.02	2.62	Oven dried
WN1-336.09	108.51	45.01	2.62	Oven dried

Table 2 - Summary of uniaxial mechanical properties of oven dried specimens

Specimen identification	Poisson's ratio	Zero pressure wave velocity (cm/sec) B.C.*	Zero pressure wave velocity (cm/sec) A.C.**	Dynamic modulus (GPa) A.C.	Confining pressure (MPa)	Axial stress rate (MPa/sec)	Triaxial strength (MPa)	Tangent modulus (GPa)
WN1-74.36	0.28	4.70	4.47	50.03	0.10	1.35	175	67.21
WN1-76.36	0.18	5.00	4.89	67.39	0.10	1.14	216	67.70
WN1-77.30	0.28	5.34	4.97	67.29	0.10	0.70	201	75.63
WN1-78.69	0.28	4.91	4.75	59.91	0.10	1.10	190	68.22
WN1-335.54	0.29	4.63	4.60	53.66	0.10	1.39	212	62.79
WN1-335.76	0.28	4.73	4.66	57.12	0.10	1.39	201	66.79
WN1-335.87	0.24	4.73	4.59	54.26	0.10	1.28	211	65.60
WN1-335.98	0.18	4.68	4.65	57.58	0.10	1.53	181	63.00
WN1-336.09	0.24	4.66	4.62	55.33	0.10	1.52	199	64.32

*B.C. - Before conditioning.

**A.C. - After conditioning.

Table 3 - Summary of uniaxial mechanical properties of surface air dried specimens

Specimen identification	Poisson's ratio	Zero pressure wave velocity (cm/sec) B.C.	Zero pressure wave velocity (cm/sec) A.C.	Dynamic modulus (GPa) A.C.	Confining pressure (MPa)	Axial stress rate (MPa/sec)	Triaxial strength (MPa)	Tangent modulus (GPa)
WW1-74.03	0.28	4.77	4.77	61.27	0.10	1.15	209	67.54
WN1-74.25	0.30	4.60	4.60	53.94	0.10	1.37	180	62.70
WN1-74.76	0.44	4.70	4.70	50.96	0.10	1.11	176	62.64
WN1-75.05	0.20	4.71	4.71	61.78	0.10	0.81	199	64.57
WN1-75.27	0.25	4.95	4.95	68.64	0.10	0.91	190	68.58
WN1-76.03	0.24	4.74	4.74	60.37	0.10	1.56	197	70.37
WN1-76.25	0.24	4.63	4.63	60.54	0.10	1.32	208	68.28
WN1-76.63	0.26	4.91	4.91	66.72	0.10	1.05	218	71.02
WN1-76.74	0.37	4.90	4.90	65.58	0.10	1.58	208	81.16
WN1-78.00	0.23	4.90	4.90	66.68	0.10	1.50	205	71.39
WN1-78.11	0.23	4.81	4.81	65.96	0.10	1.47	206	71.39
WN1-79.41	0.30	4.60	4.60	58.86	01.10	1.28	199	71.80

Table 4 - Summary of uniaxial mechanical properties of saturated specimens

Specimen identification	Poisson's ratio	Zero pressure wave velocity (cm/sec) B.C.	Zero pressure wave velocity (cm/sec) A.C.	Dynamic modulus (GPa) A.C.	Confining pressure (MPa)	Axial stress rate (MPa/sec)	Triaxial strength (MPa)	Tangent modulus (GPa)
WN1-74.14	0.26	N/A	5.91	119.84	0.10	1.34	188	61.99
WN1-74.54	0.27	N/A	6.06	125.99	0.10	1.68	190	74.50
WN1-74.65	0.36	N/A	6.16	131.93	0.10	1.51	178	73.37
WN1-75.16	0.27	N/A	5.86	117.28	0.10	1.26	172	71.95
WN1-76.85	0.29	N/A	5.92	118.57	0.10	1.32	218	72.66
WN1-78.22	0.28	N/A	6.11	126.55	0.10	1.39	213	75.26
WN1-78.36	0.25	N/A	5.93	121.35	0.10	1.30	216	67.37
WN1-78.47	0.28	4.70	5.97	121.72	0.10	2.00	210	71.26
WN1-79.30	0.28	N/A	5.79	114.18	0.10	1.03	184	73.68
WN1-79.52	0.26	N/A	5.88	120.49	0.10	1.67	215	70.40

Table 5 - Mean mechanical properties of WN1 core

Mean mechanical properties	Initial conditioning: Oven dried	Surface air dried	Saturated
Compressive Wave Velocity (km/sec)	4.69 (σ = 0.16)	4.79 (σ = 0.17)	5.96 (σ = 0.12)
Dynamic Modulus (GPa)	58.06 (σ = 5.93)	61.78 (σ = 5.38)	121.79 (σ = 5.14)
Poisson's ratio	0.25 (σ = 0.04)	0.28 (σ = 0.07)	0.28 (σ = 0.03)
Uniaxial Compressive Strength (MPa)	198 (σ = 14)	200 (σ = 12)	198 (σ = 18)
Tangent Modulus of Elasticity (GPa)	66.81 (σ = 3.59)	69.29 (σ = 5.00)	71.24 (σ = 3.96)

Fig. 1 :Axial & Circumferential Stress Strain Curves

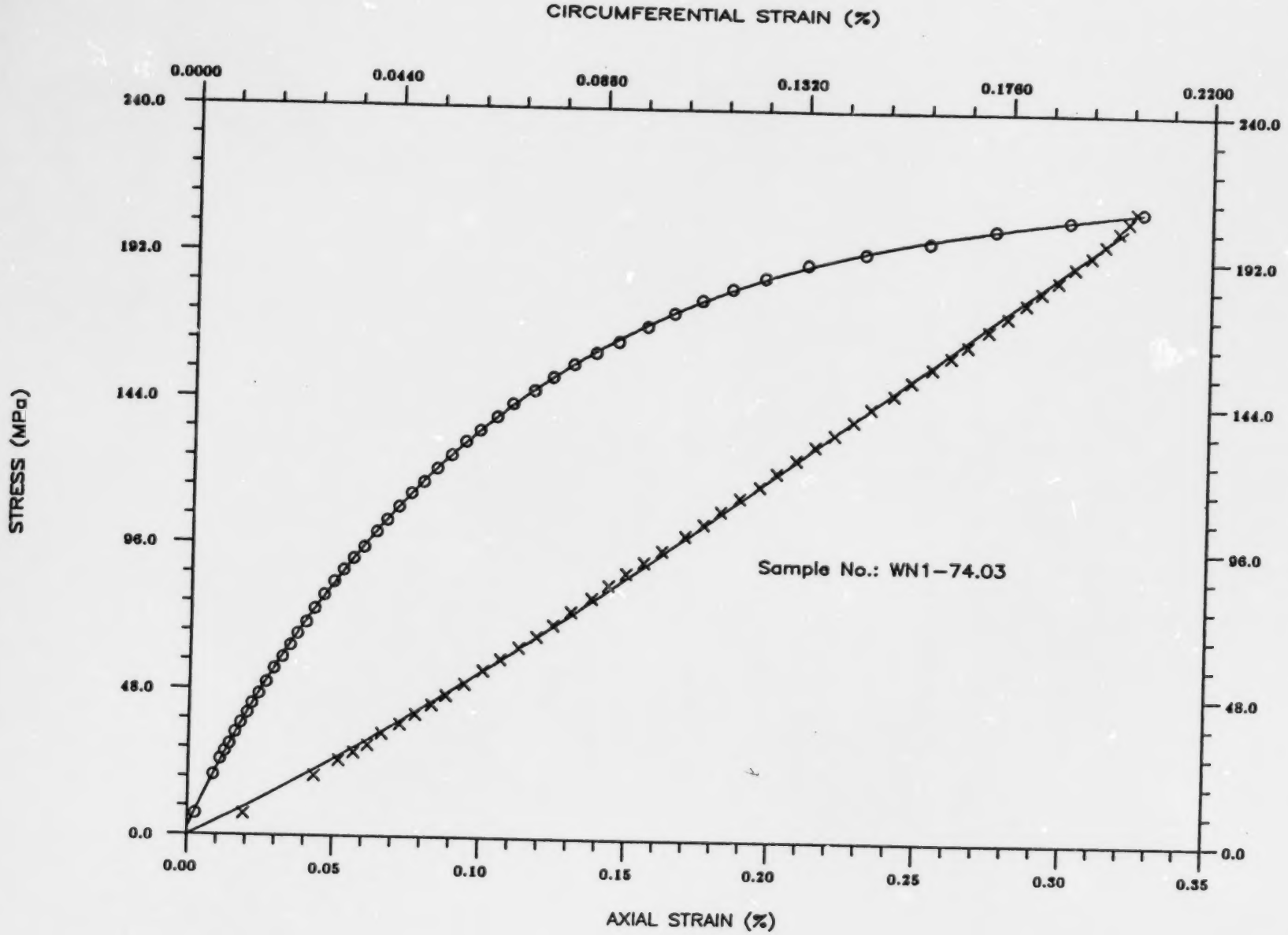

Fig. 2 :Axial & Circumferential Stress Strain Curves

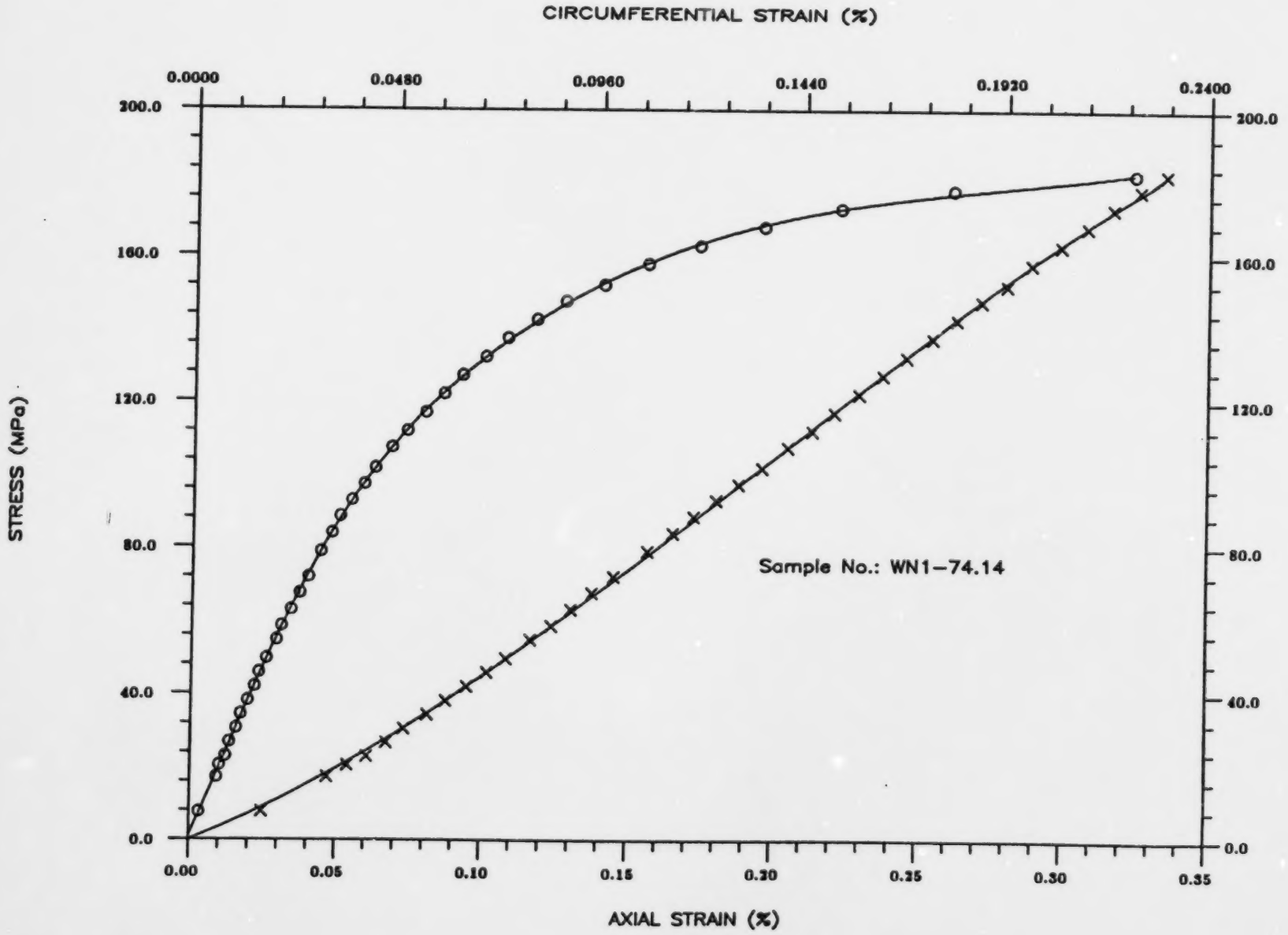

Fig. 3 :Axial & Circumferential Stress Strain Curves

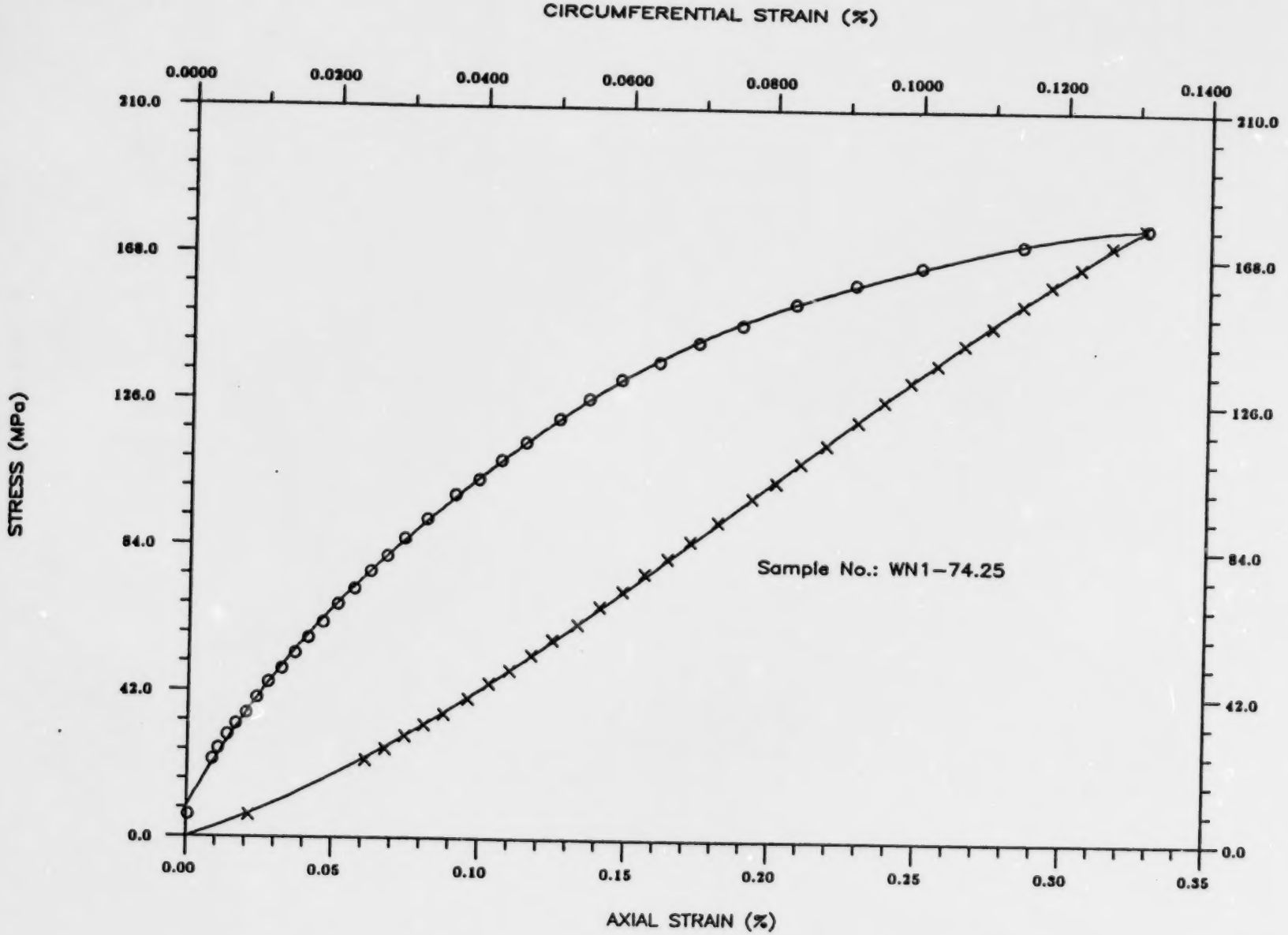

Fig. 4 :Axial & Circumferential Stress Strain Curves

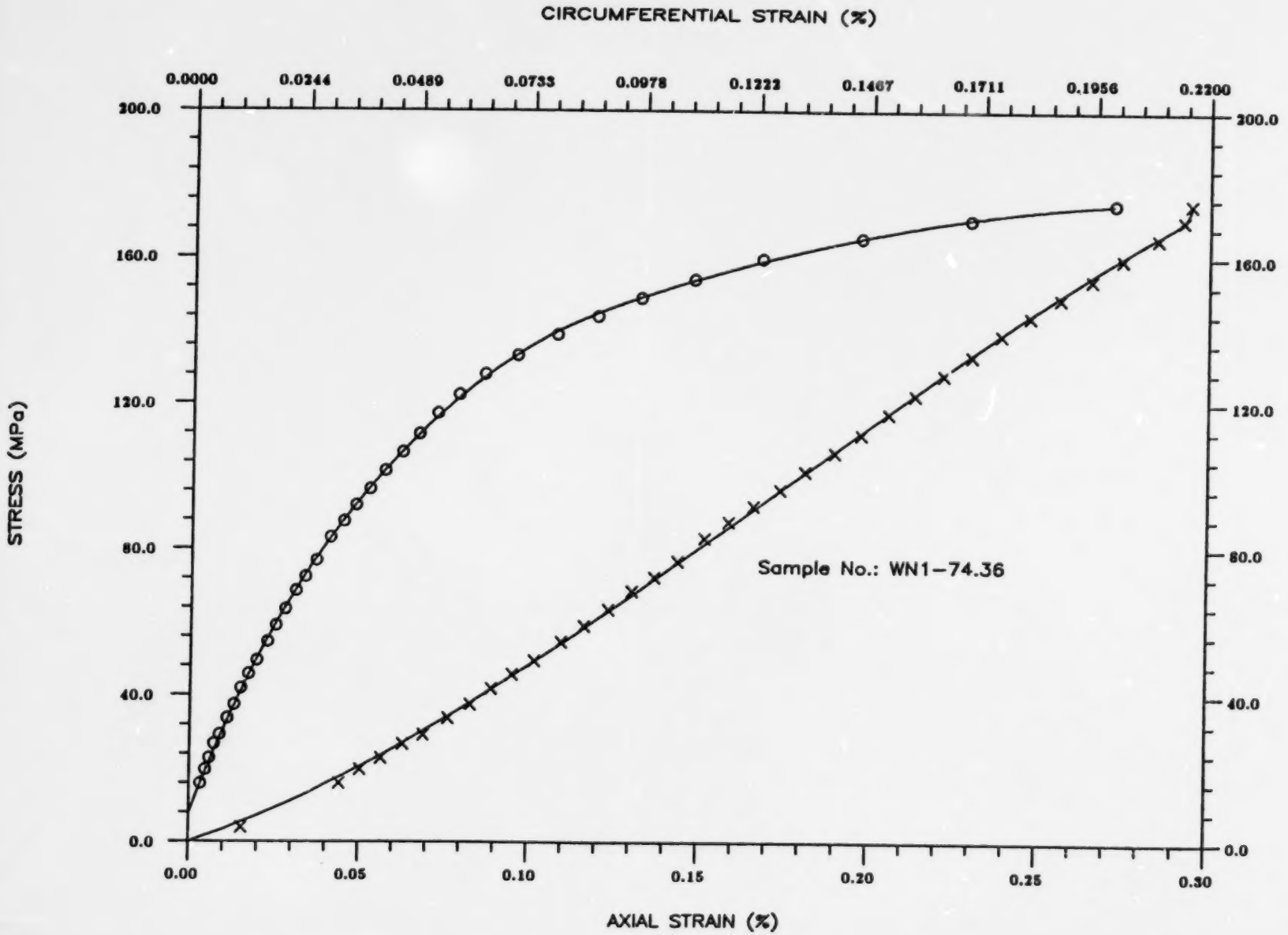

Fig. 5 :Axial & Circumferential Stress Strain Curves

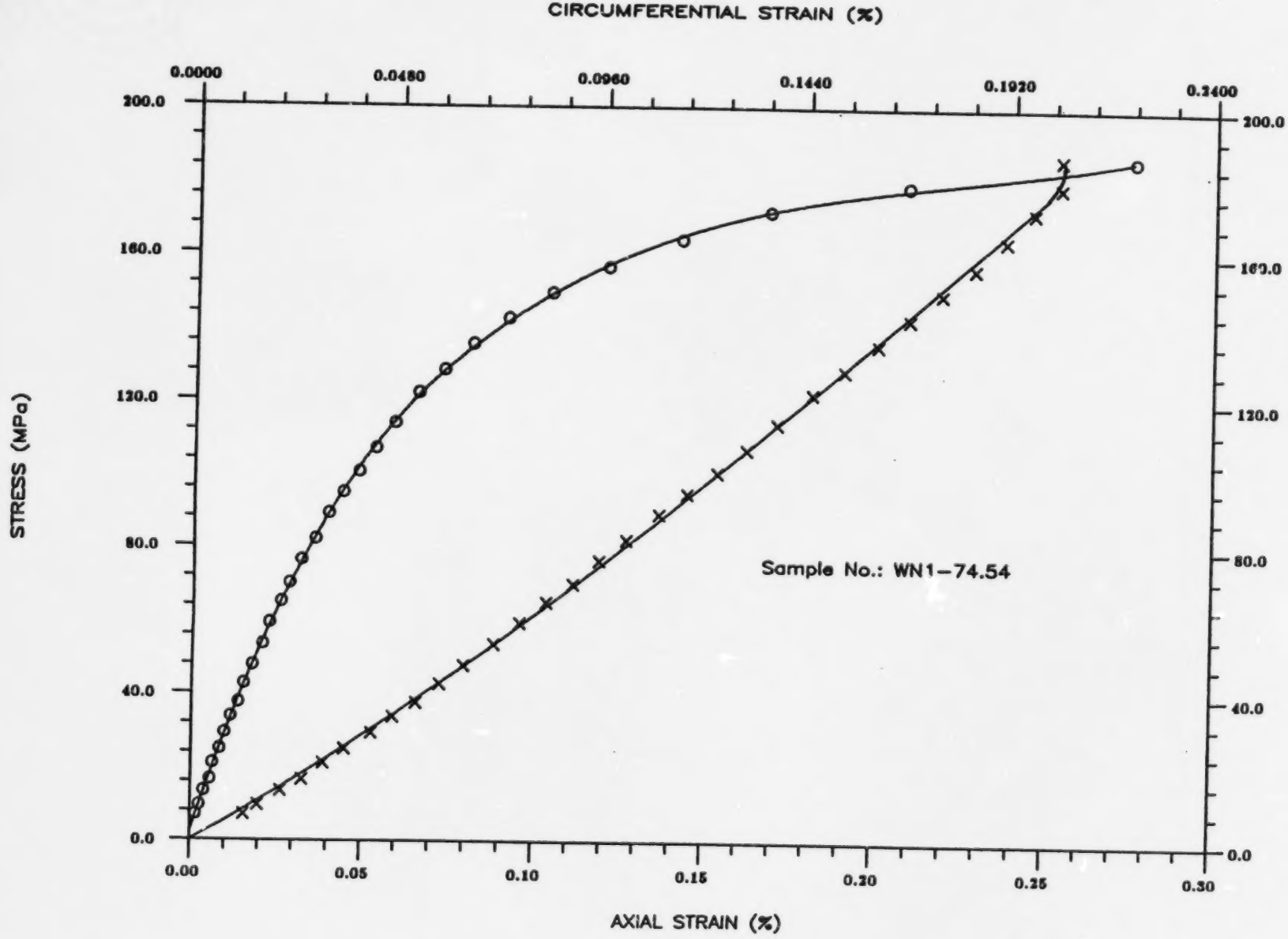

Fig. 6 :Axial & Circumferential Stress Strain Curves

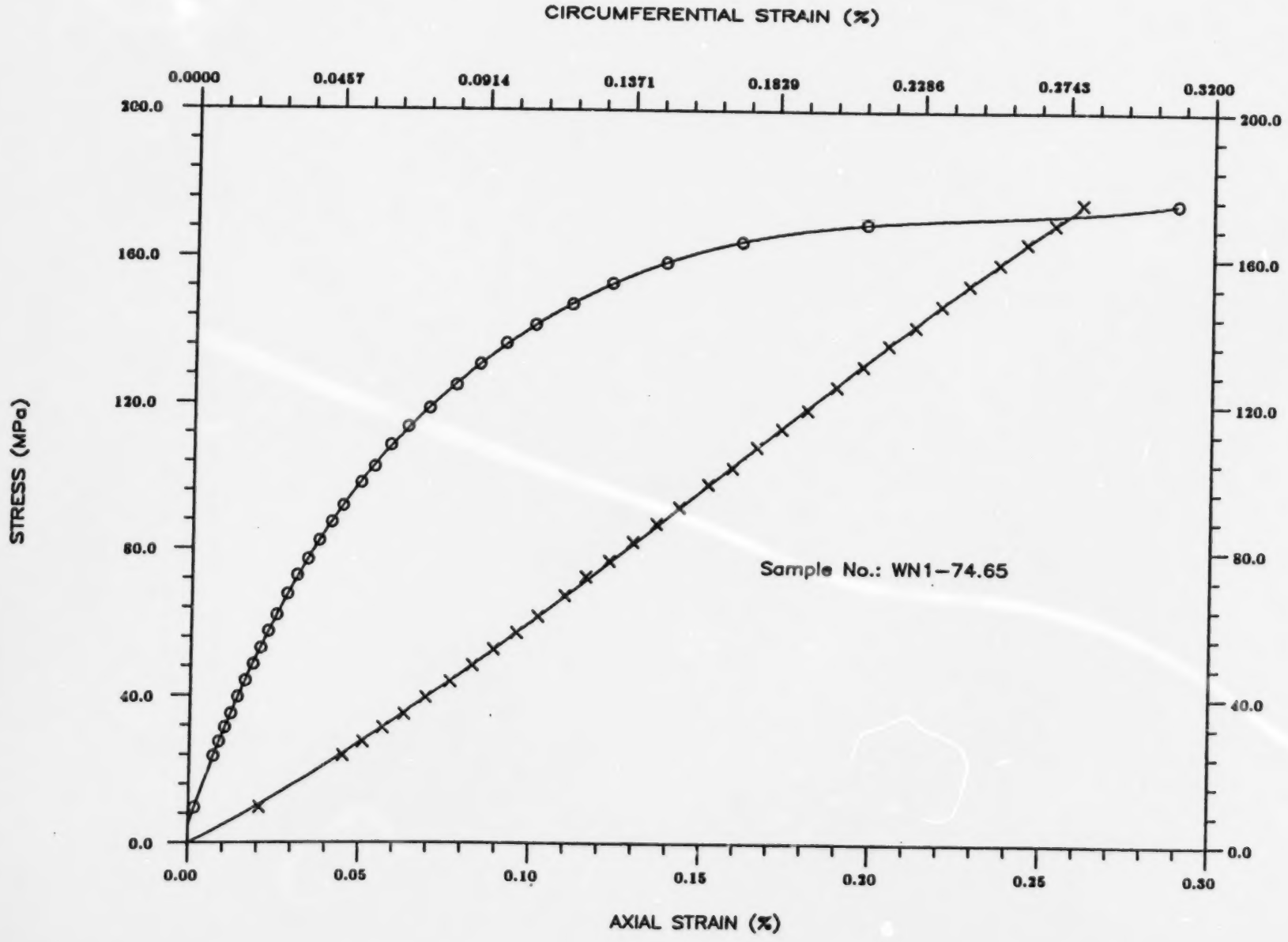

Fig. 7 :Axial & Circumferential Stress Strain Curves

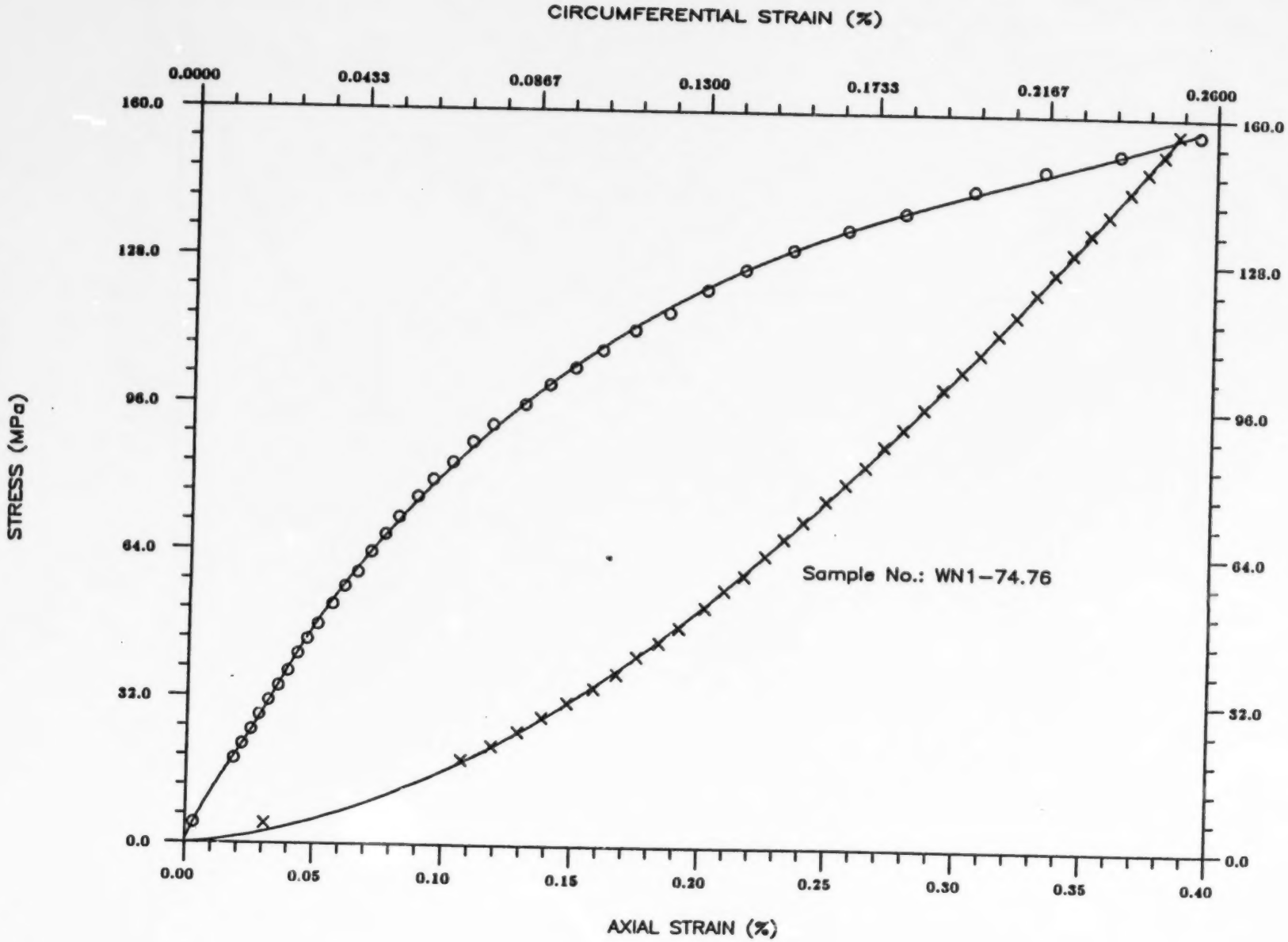

Fig. 8 :Axial & Circumferential Stress Strain Curves

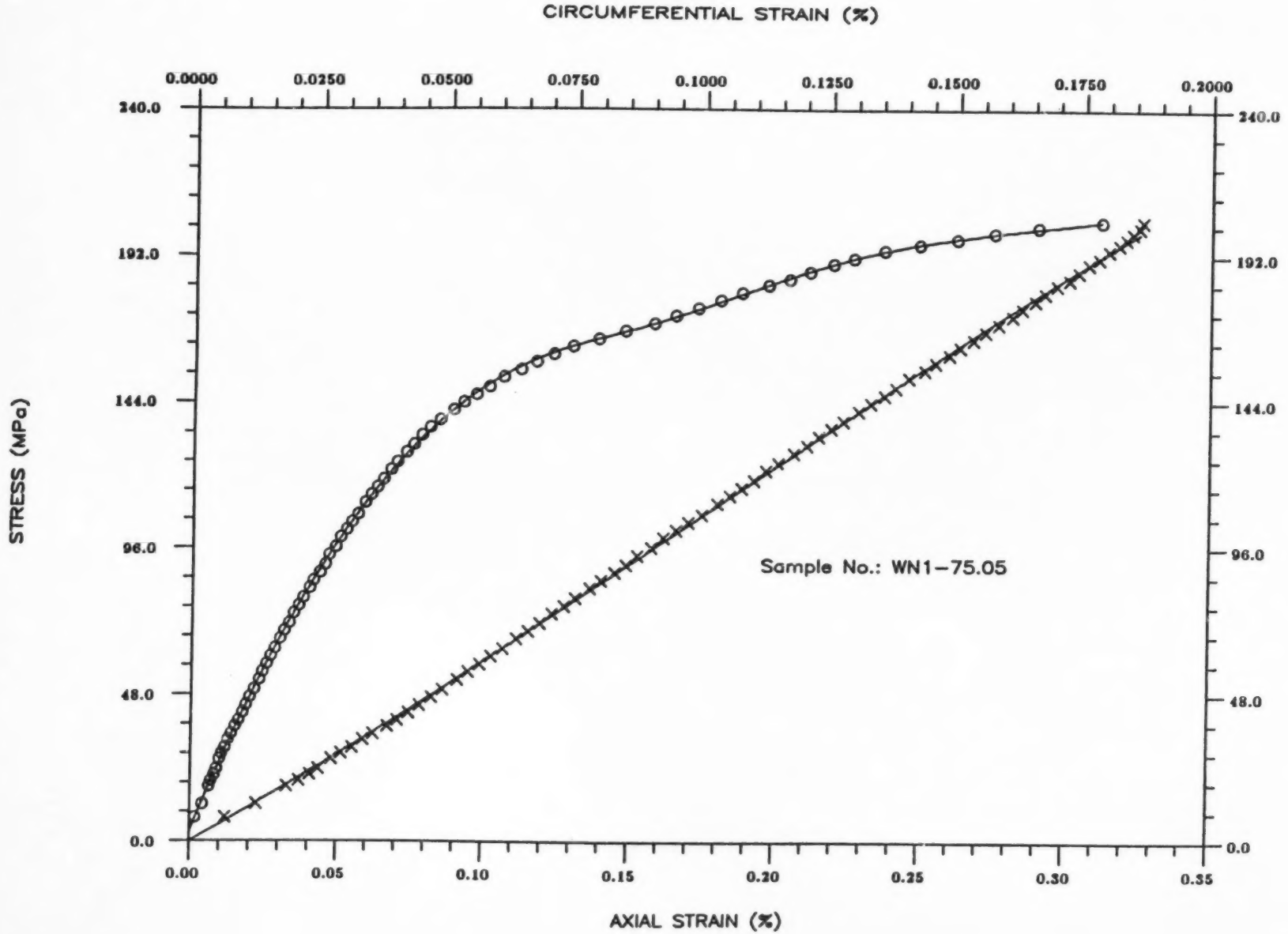

Fig. 9 :Axial & Circumferential Stress Strain Curves

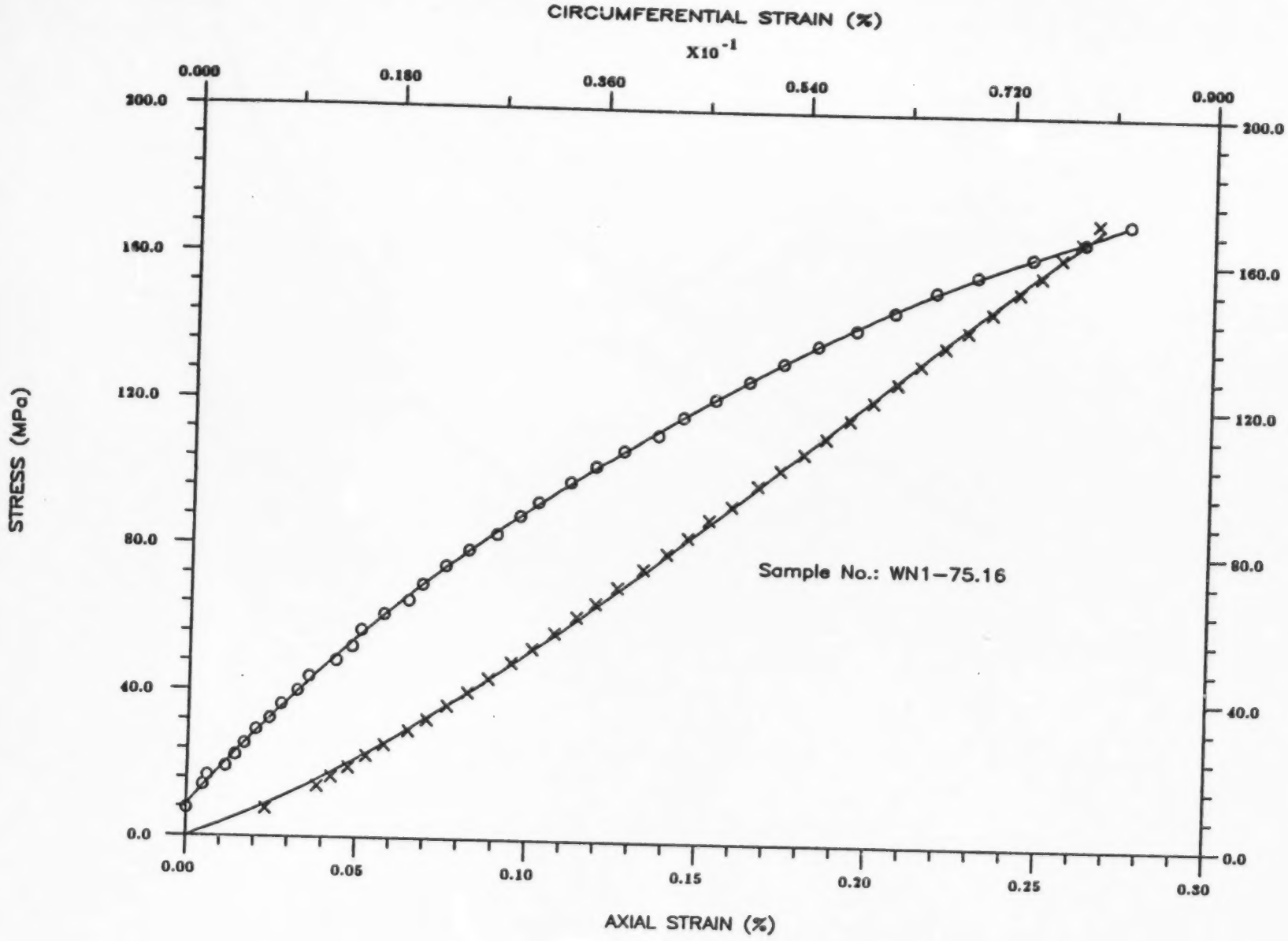

Fig.10 :Axial & Circumferential Stress Strain Curves

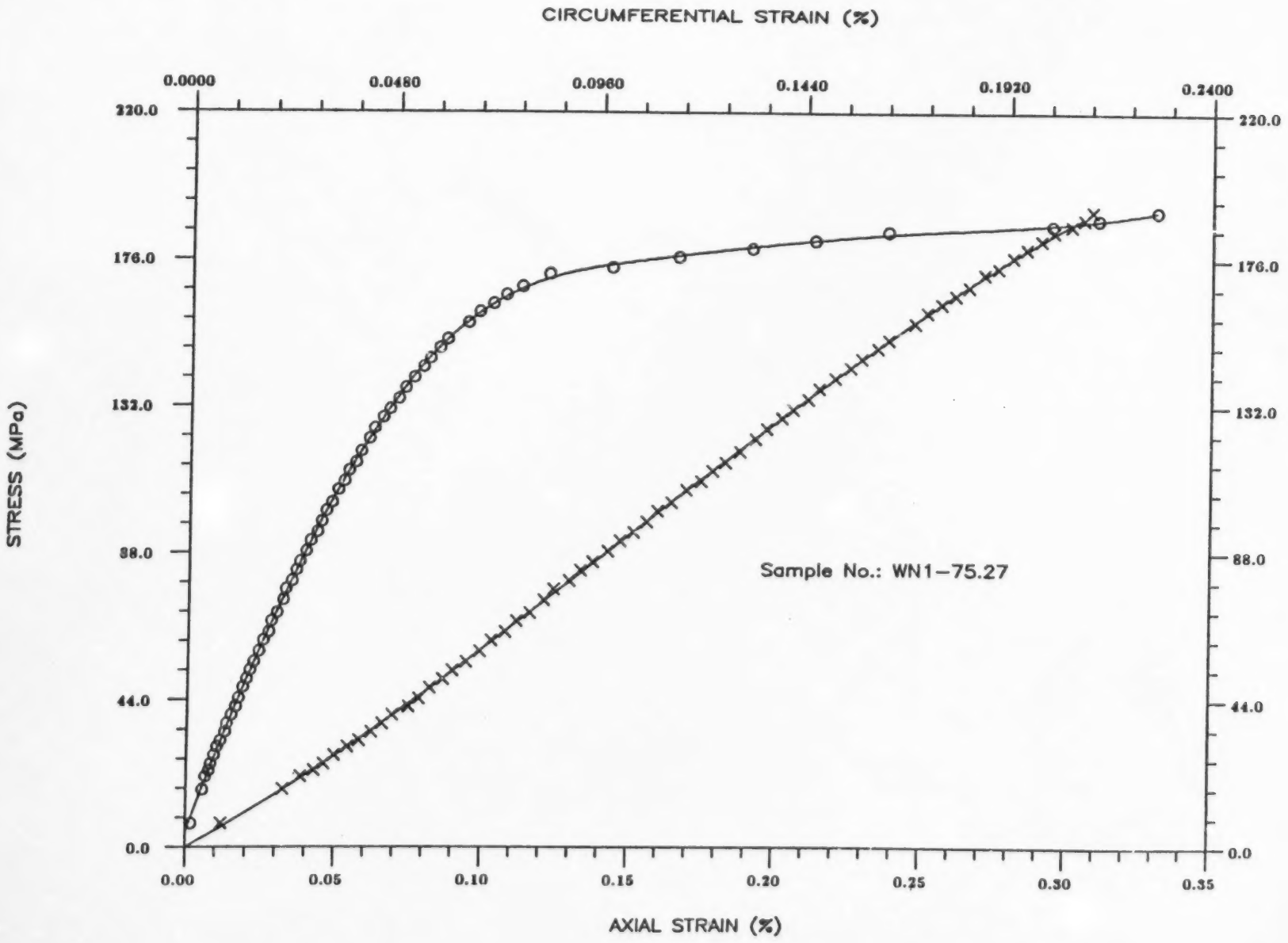

Fig. II :Axial & Circumferential Stress Strain Curves

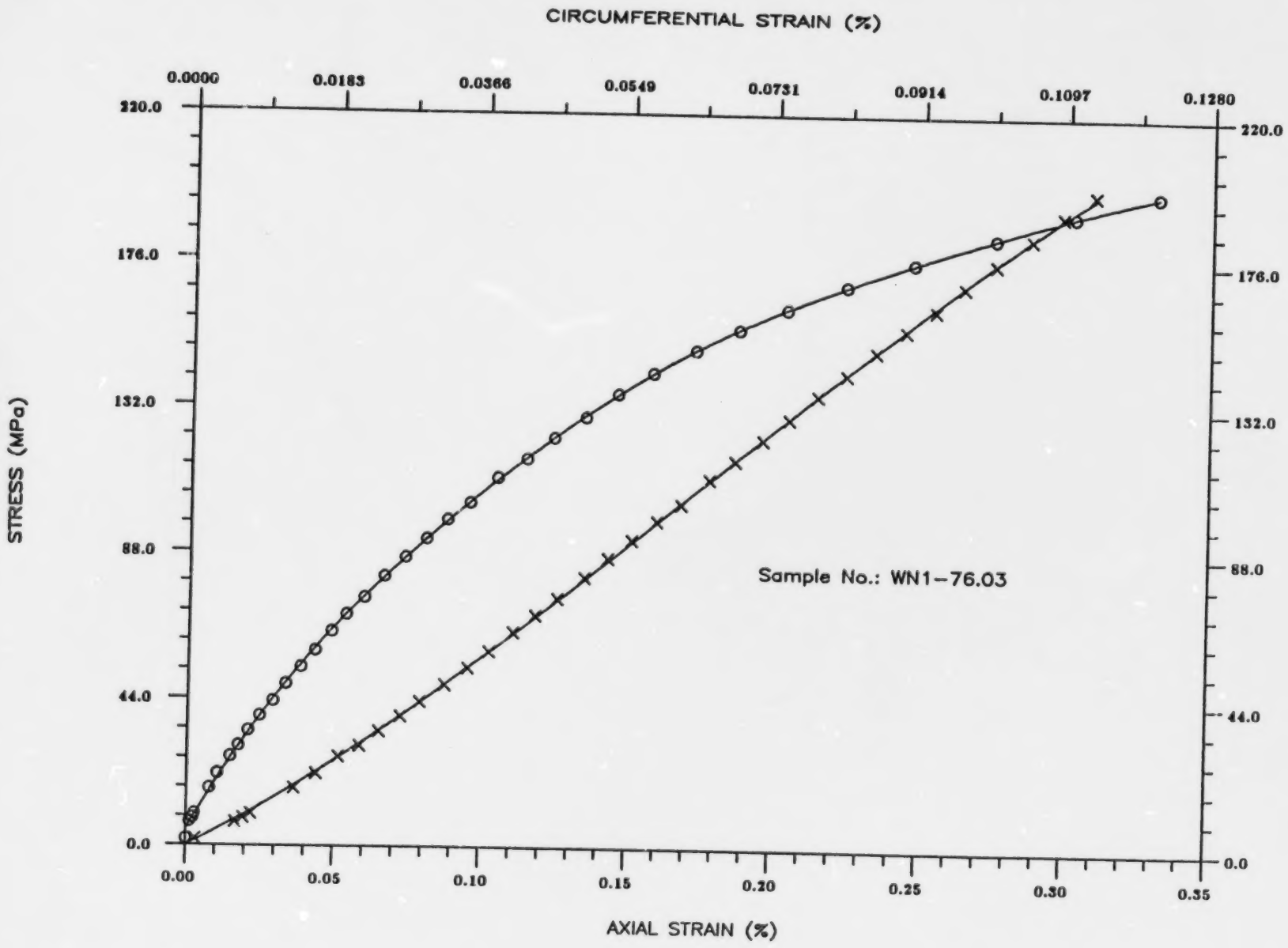

Fig. 12 :Axial & Circumferential Stress Strain Curves

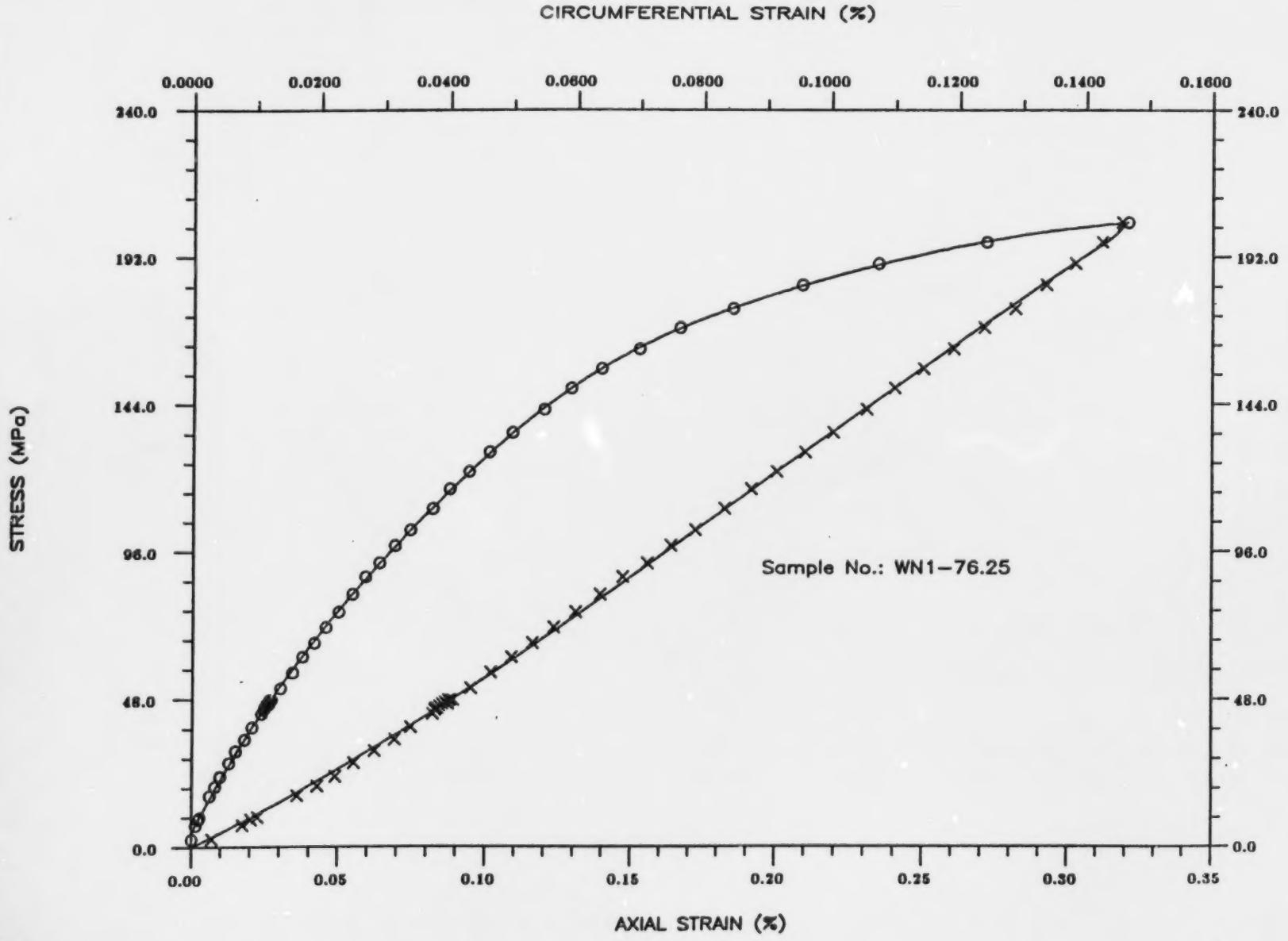

Fig.13 :Axial & Circumferential Stress Strain Curves

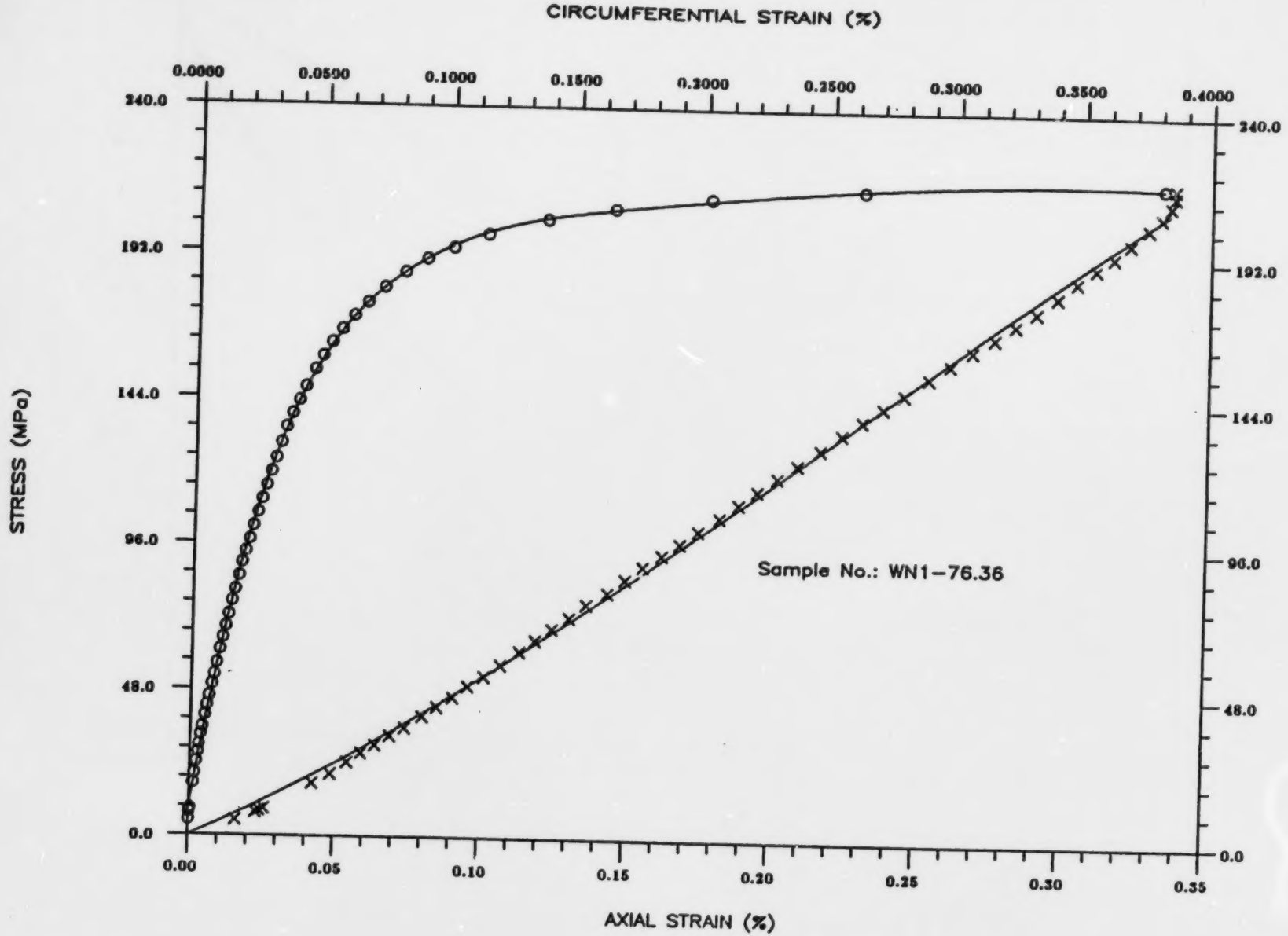

Fig.14 :Axial & Circumferential Stress Strain Curves

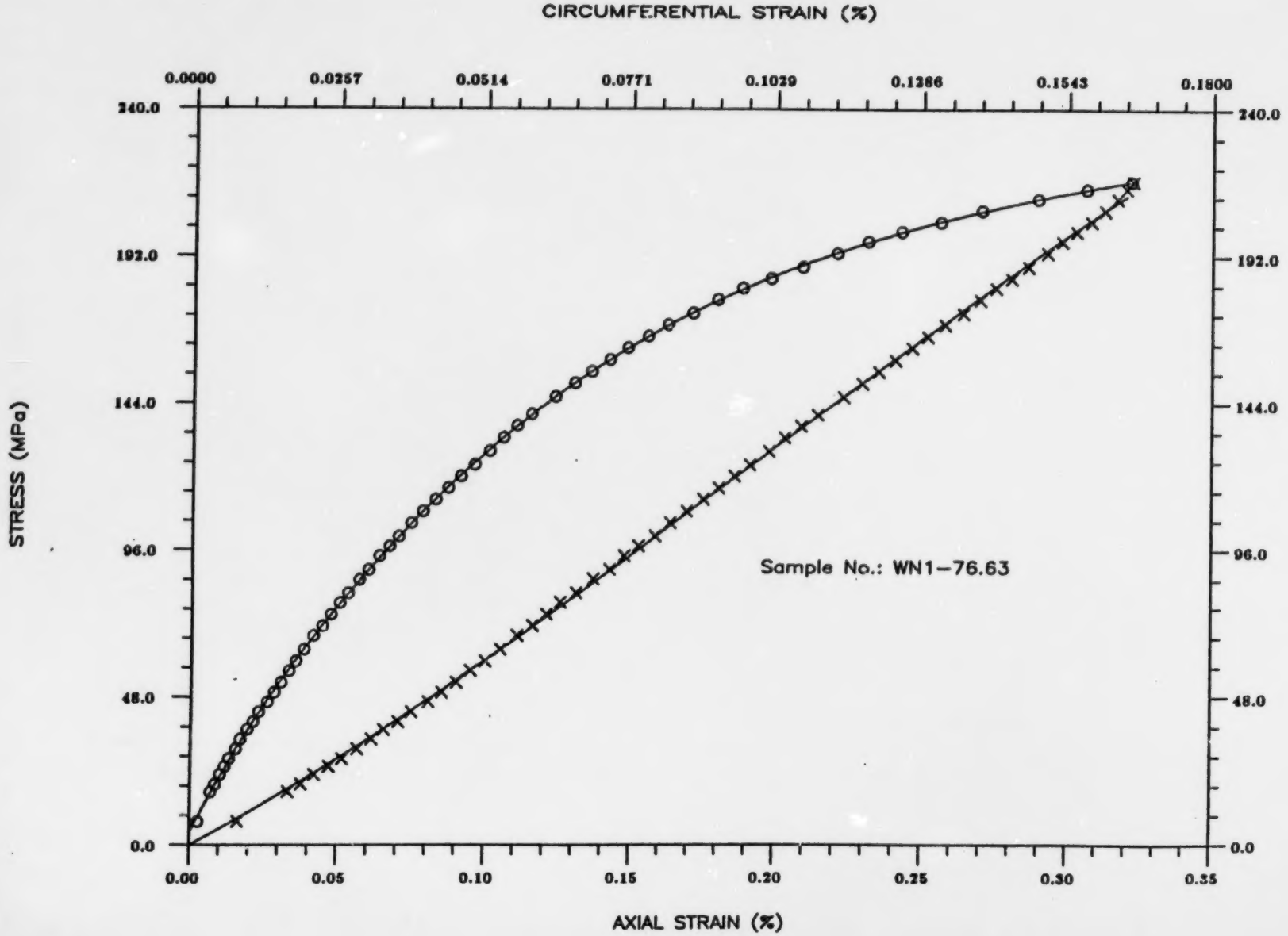

Fig. 15 :Axial & Circumferential Stress Strain Curves

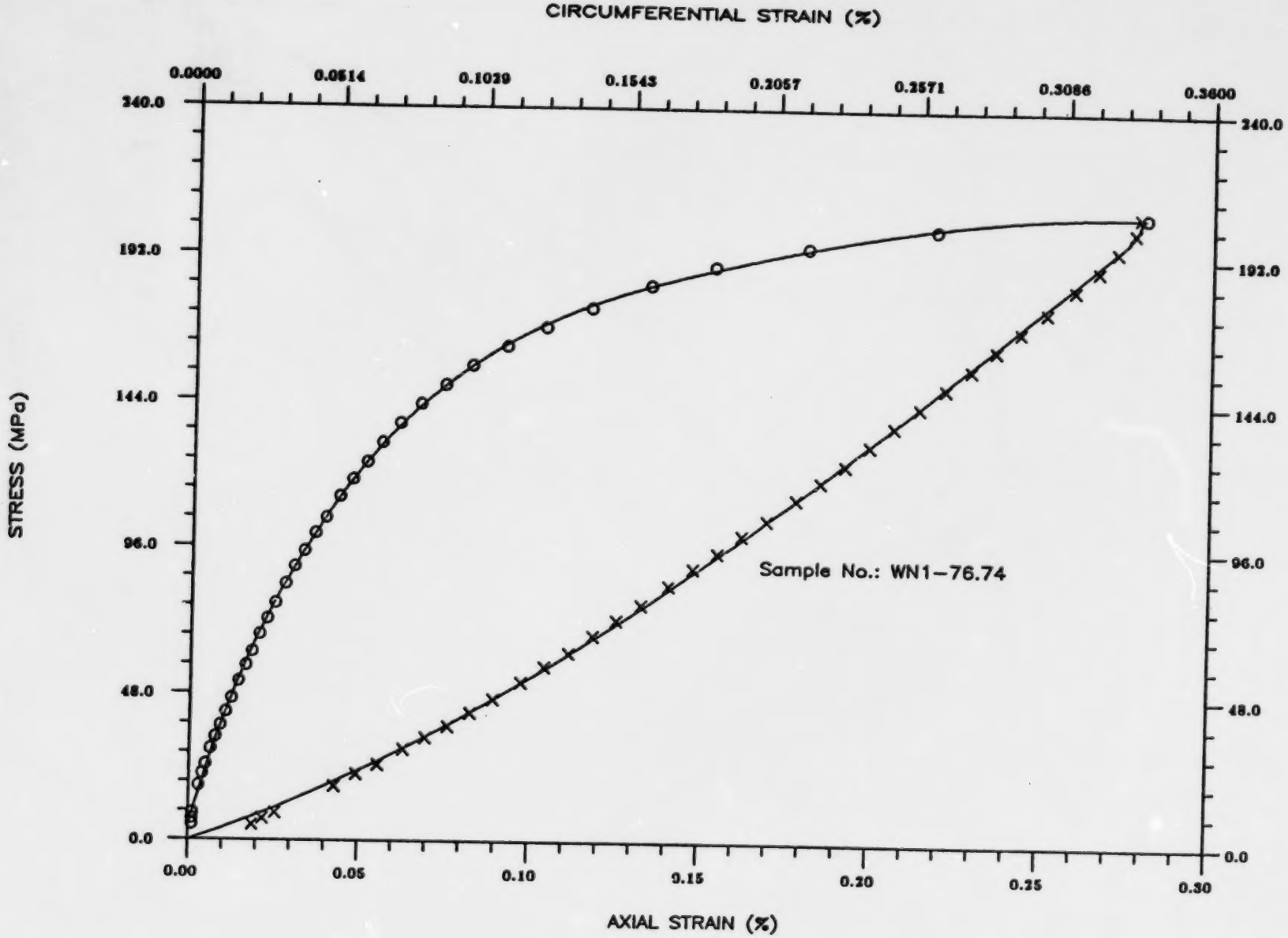

Fig. 16:Axial & Circumferential Stress Strain Curves

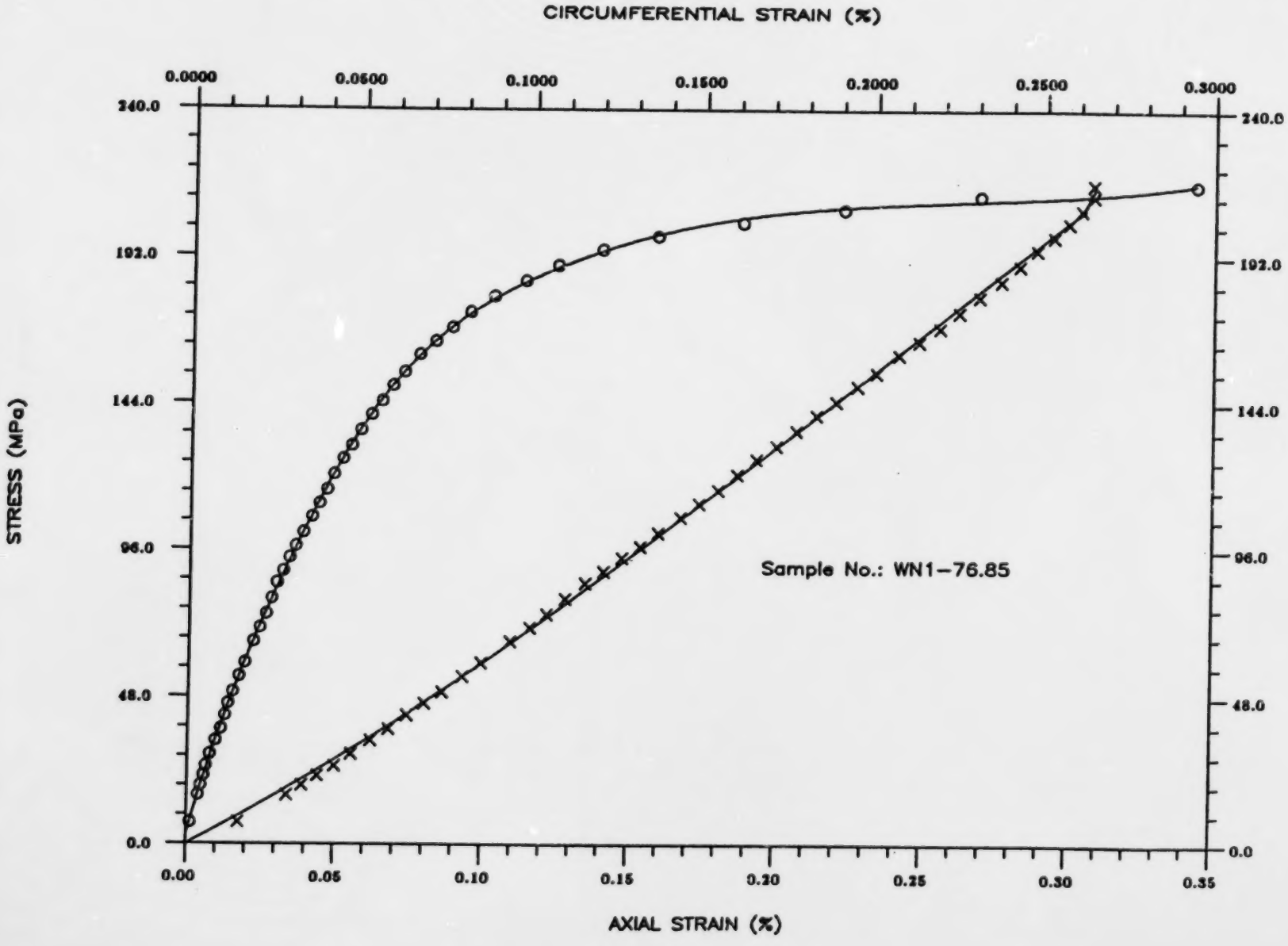

Fig.17:Axial & Circumferential Stress Strain Curves

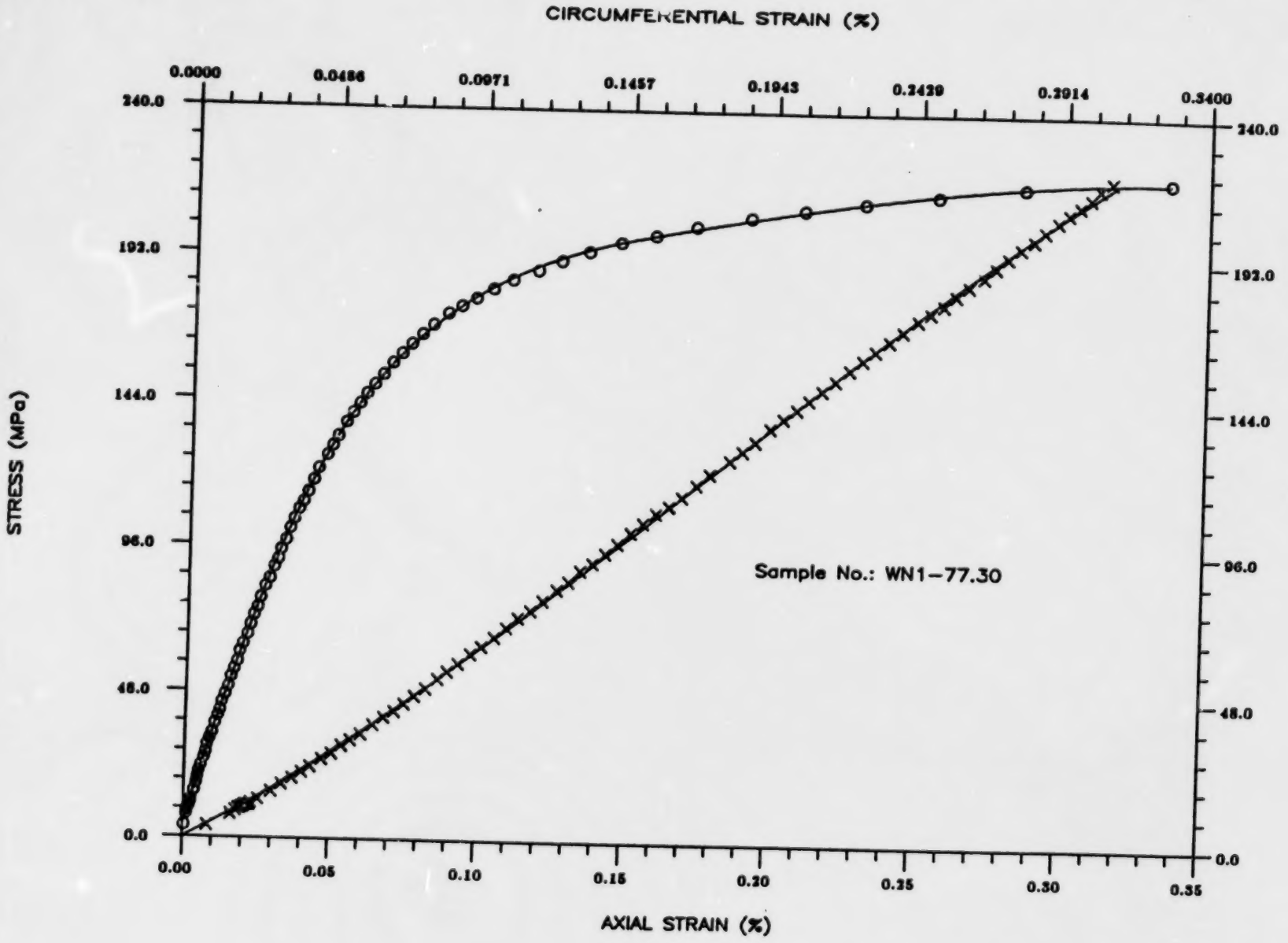

Fig. 18 :Axial & Circumferential Stress Strain Curves

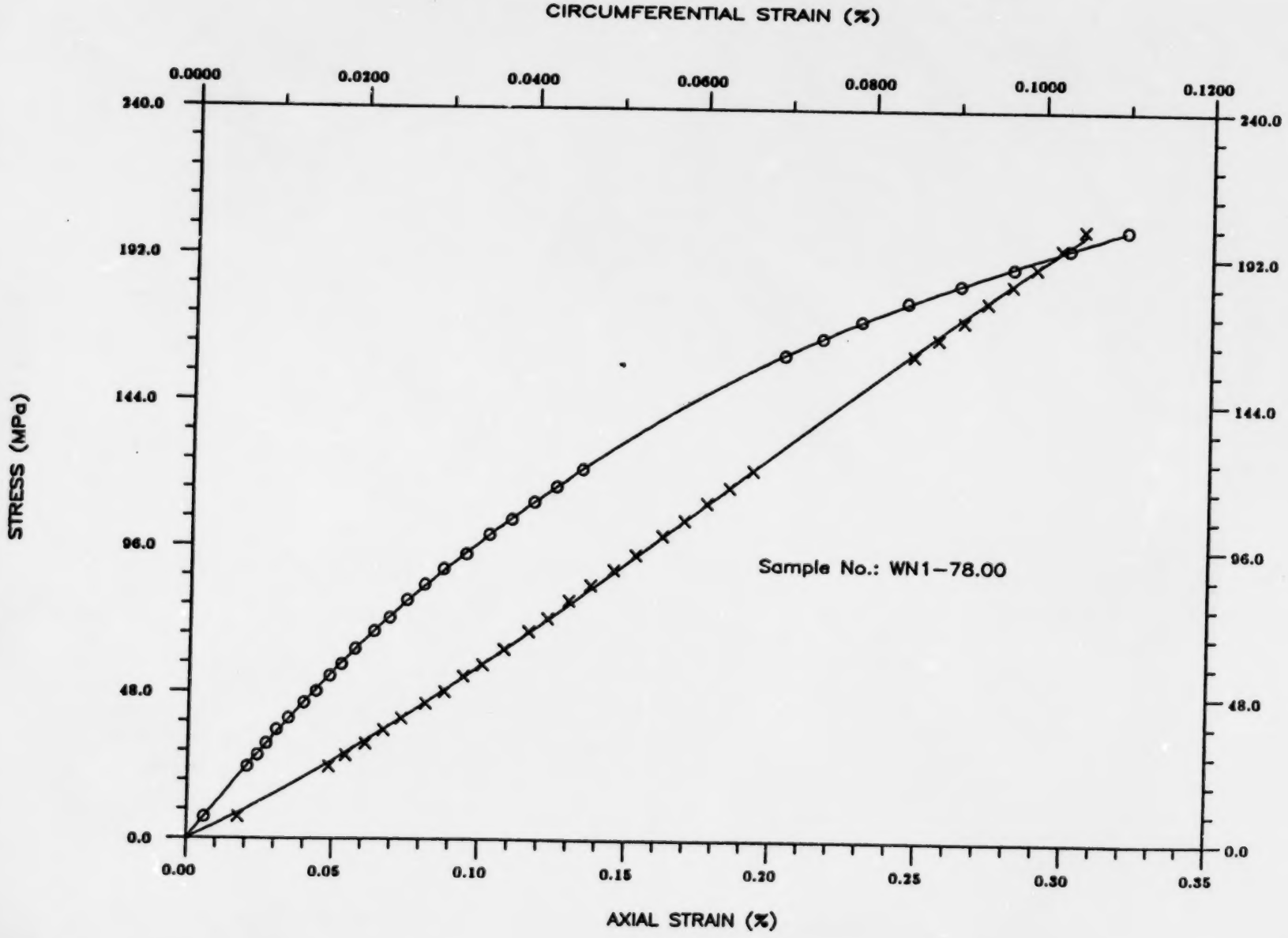

Fig.19 :Axial & Circumferential Stress Strain Curves

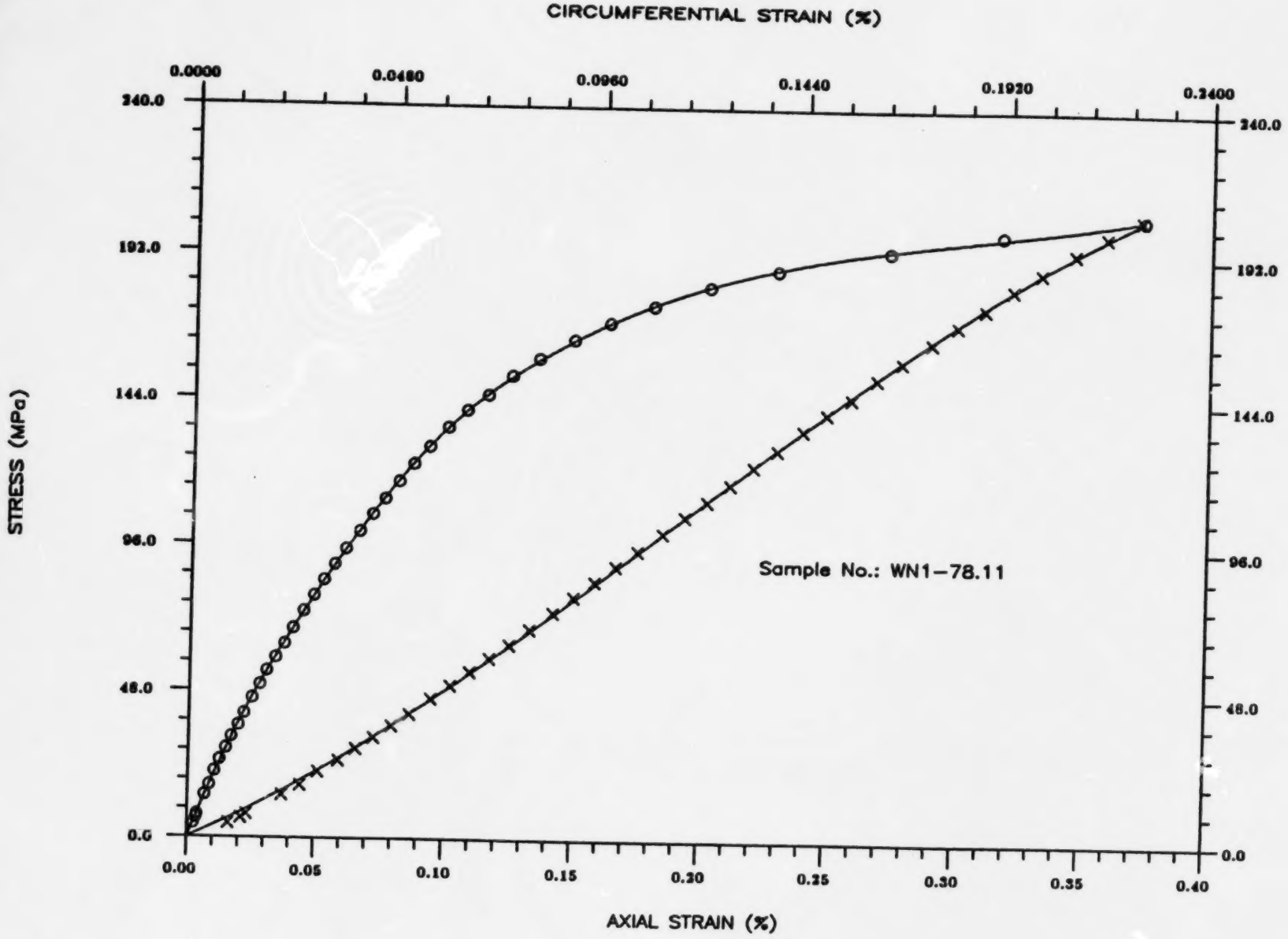

Fig.20:Axial & Circumferential Stress Strain Curves

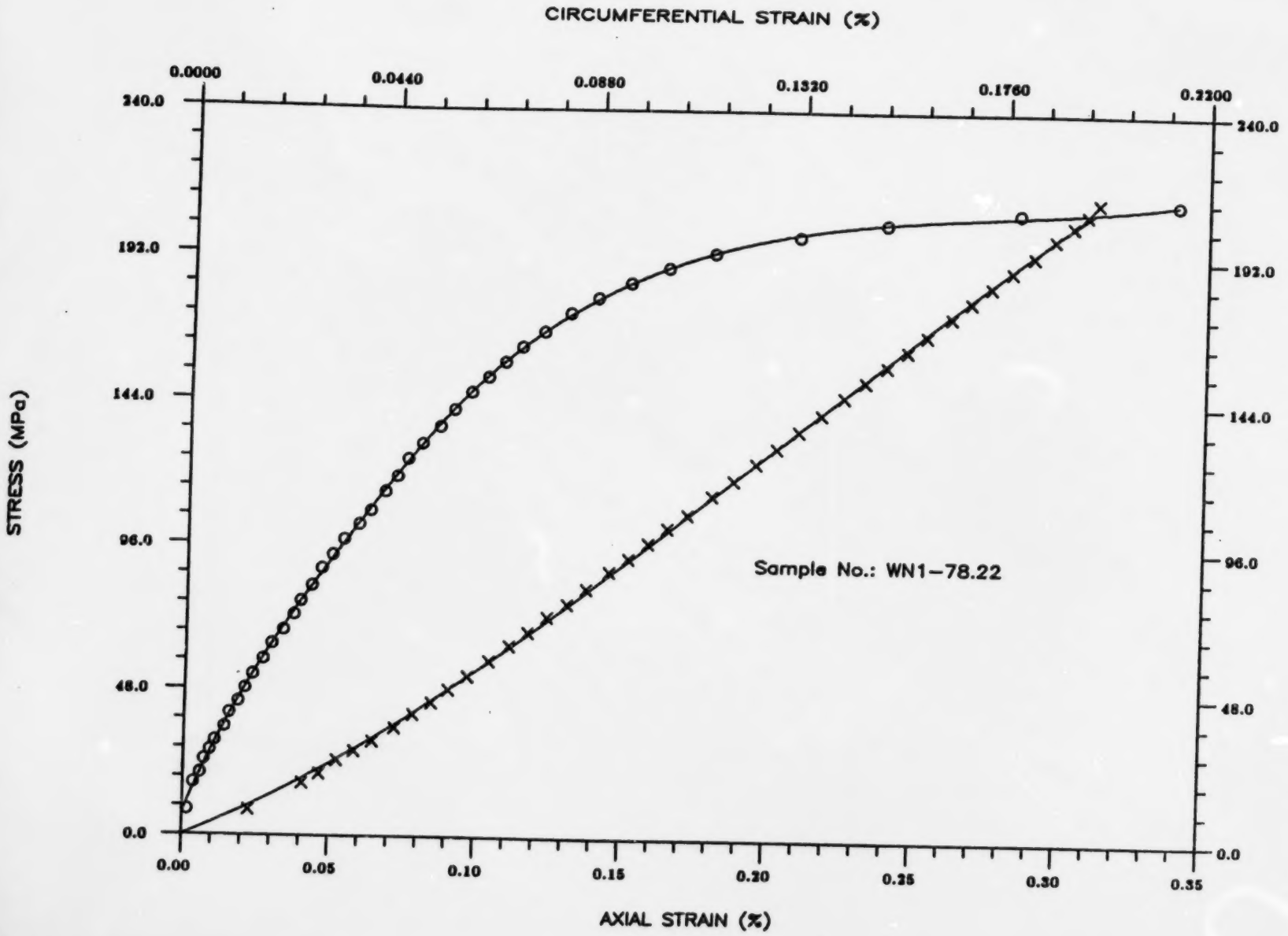

Fig.21 :Axial & Circumferential Stress Strain Curves

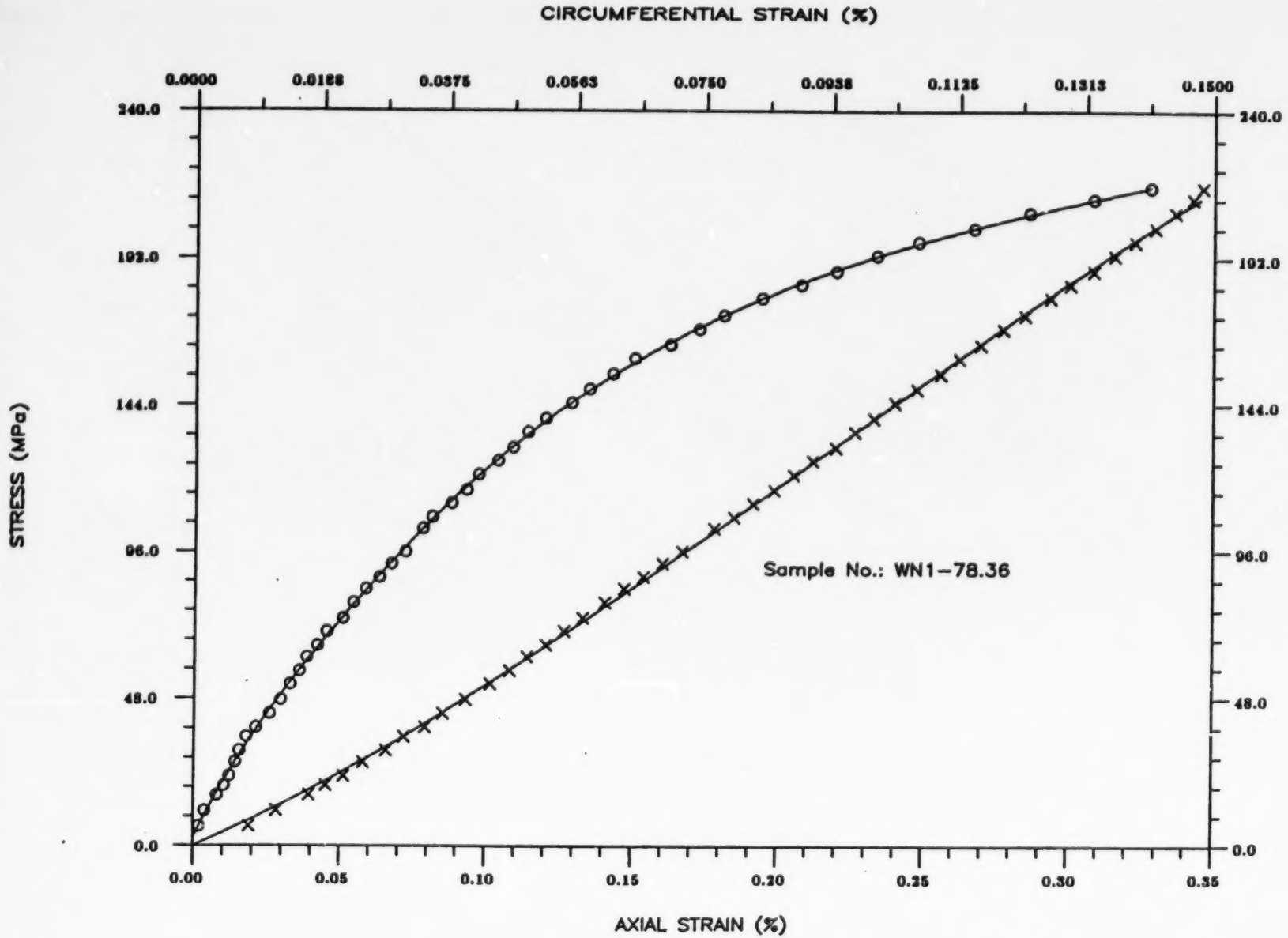

Fig. 22: Axial & Circumferential Stress Strain Curves

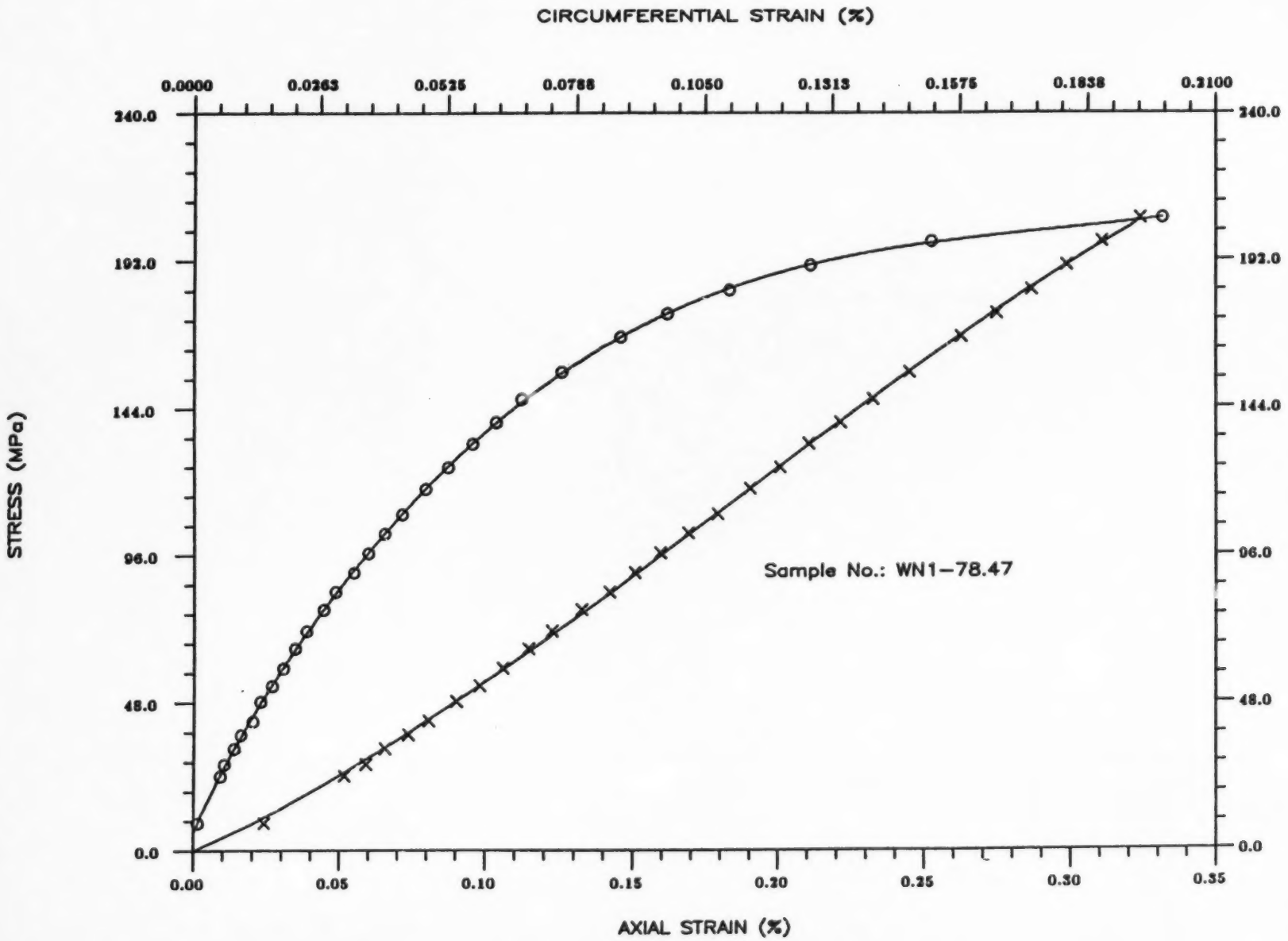

Fig.23:Axial & Circumferential Stress Strain Curves

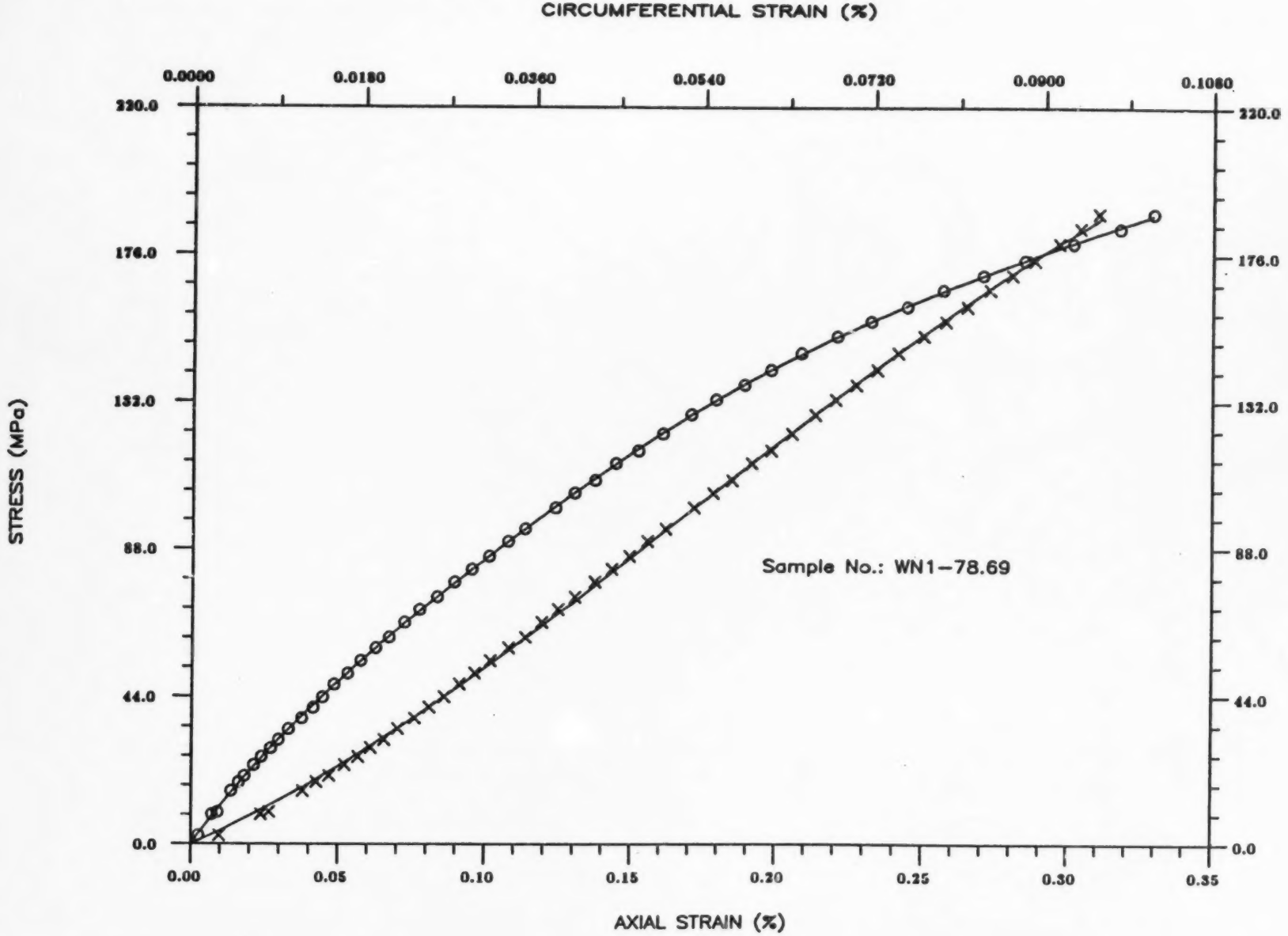

Fig.24:Axial & Circumferential Stress Strain Curves

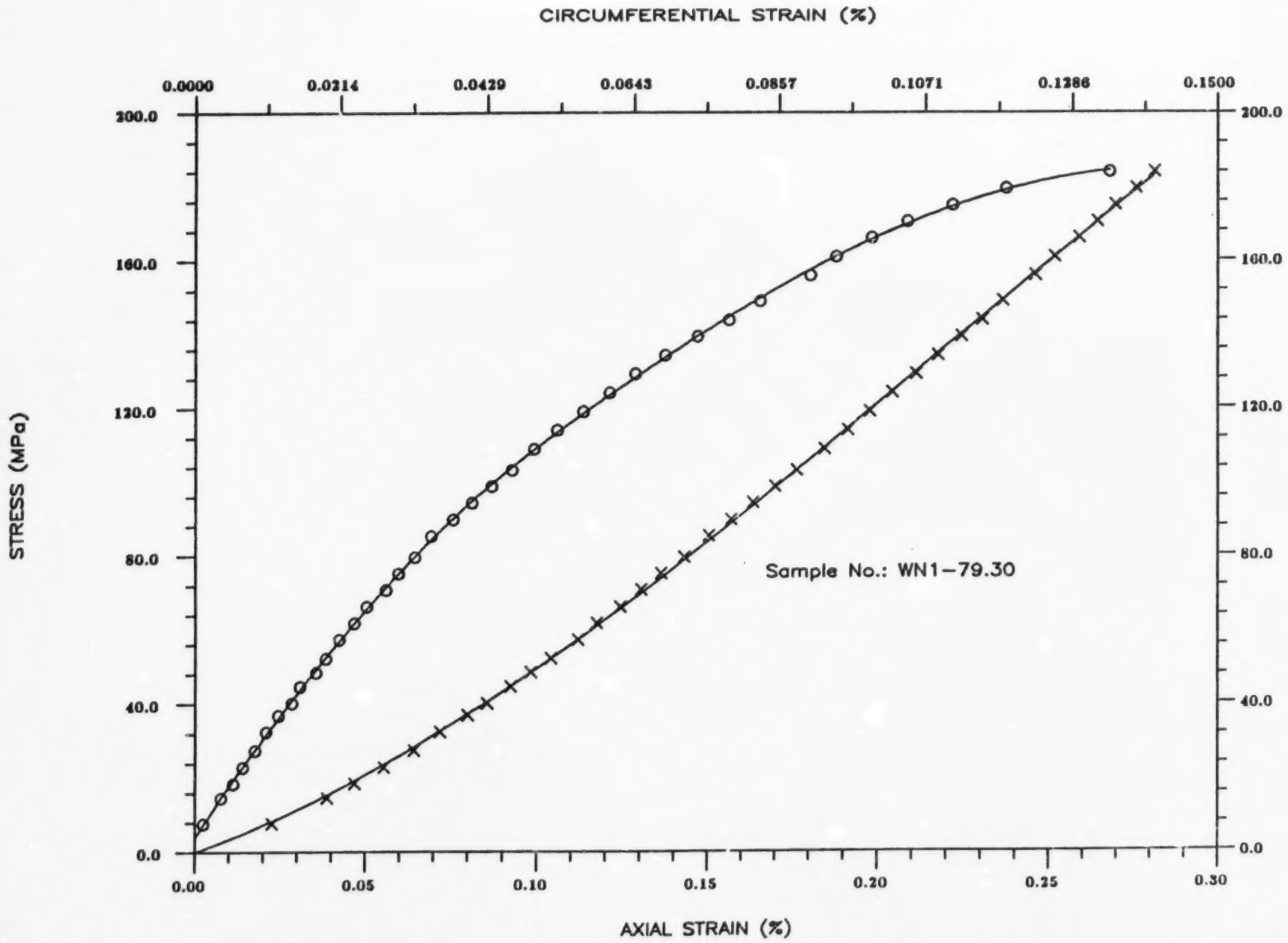

Fig.25:Axial & Circumferential Stress Strain Curves

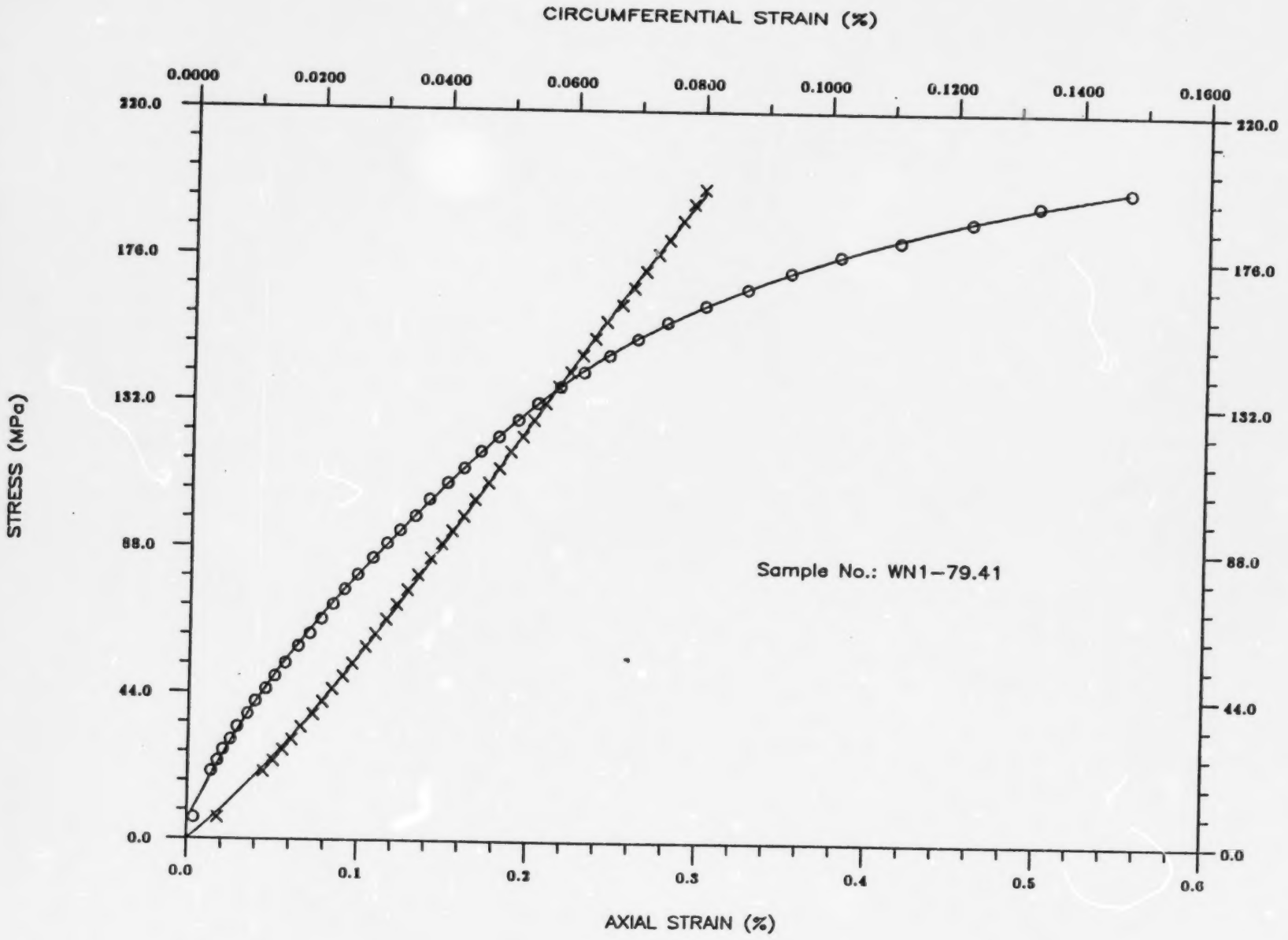

Fig.26:Axial & Circumferential Stress Strain Curves

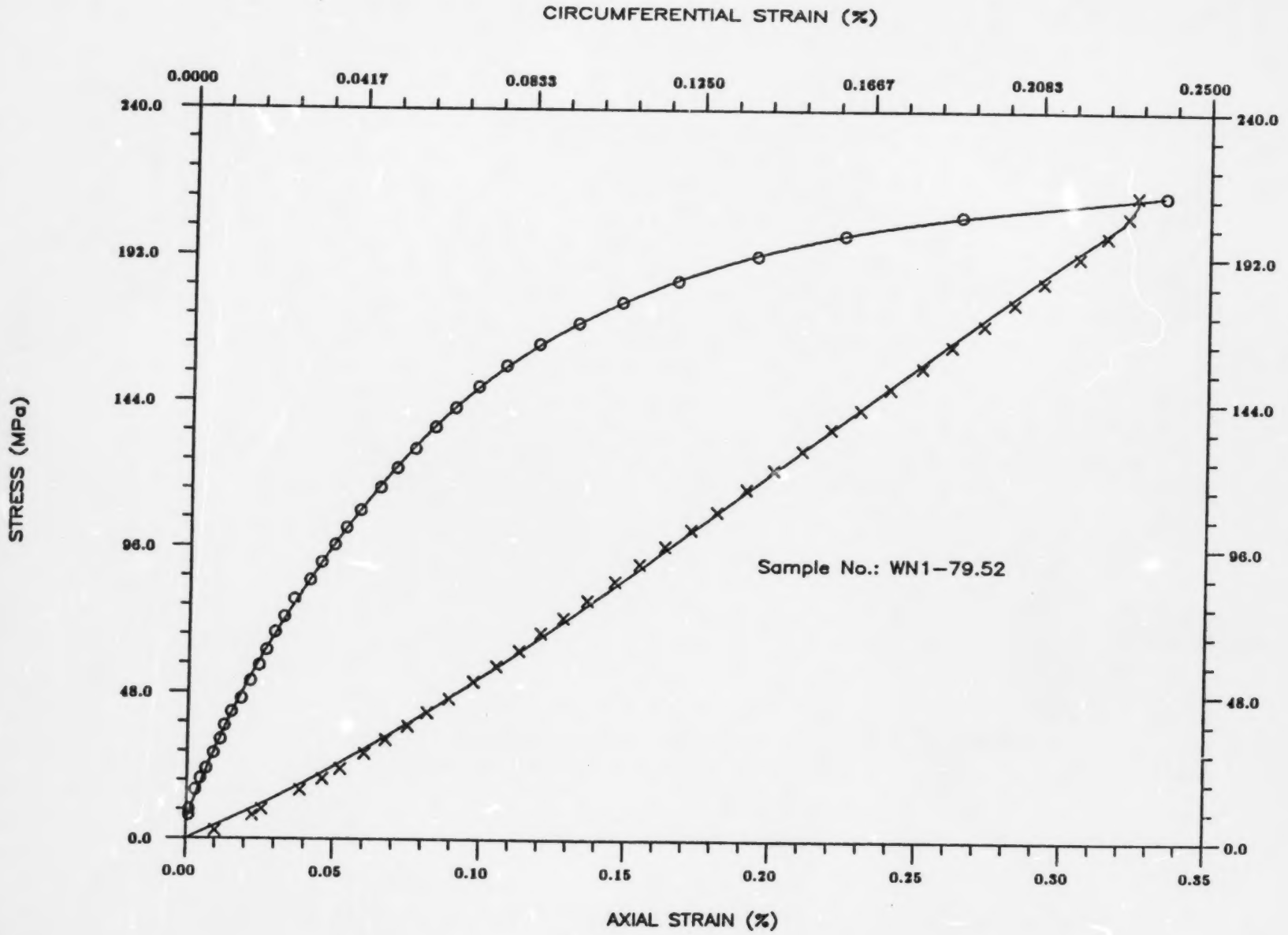

Fig.27:Axial & Circumferential Stress Strain Curves

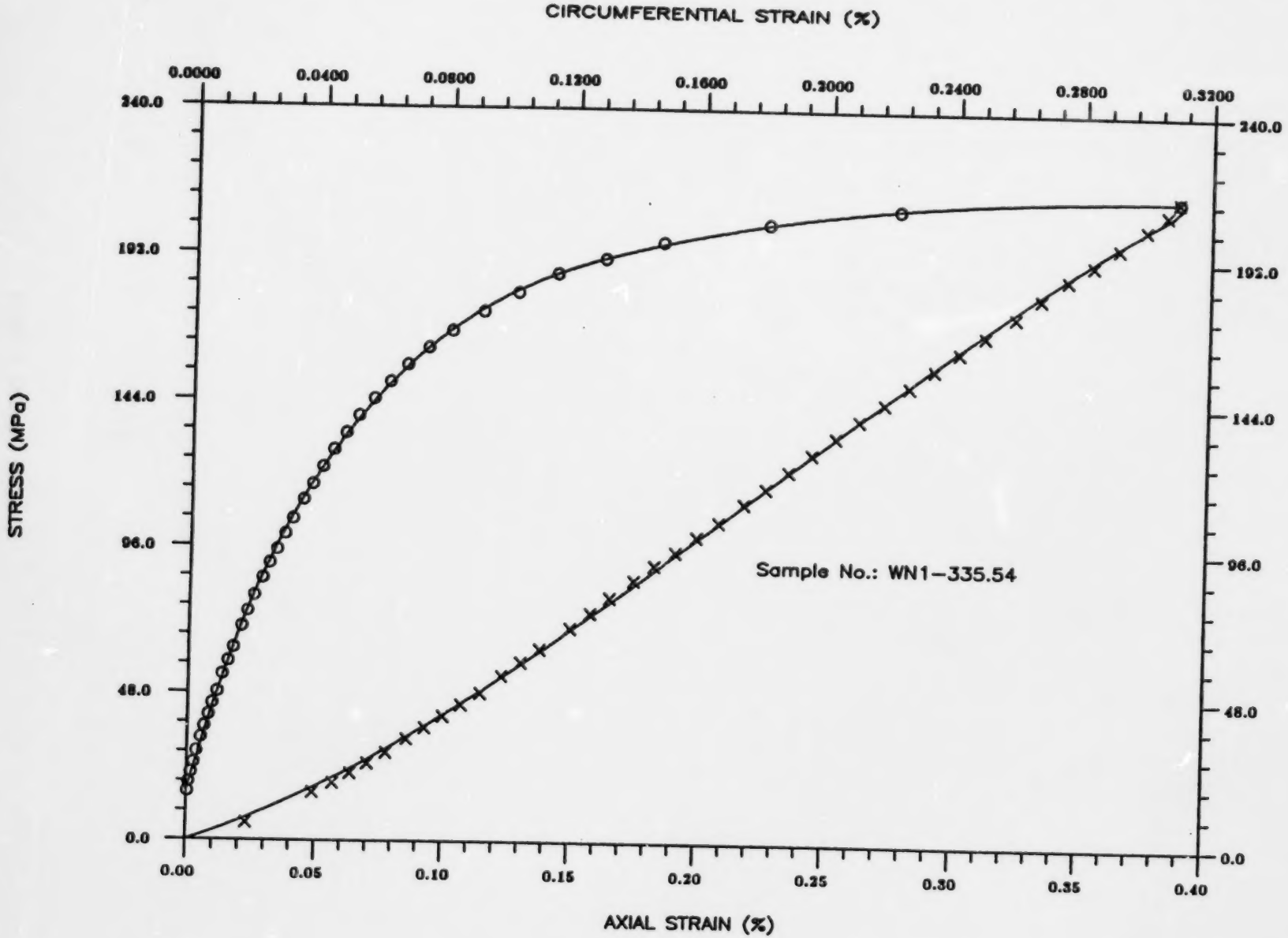

Fig.28:Axial & Circumferential Stress Strain Curves

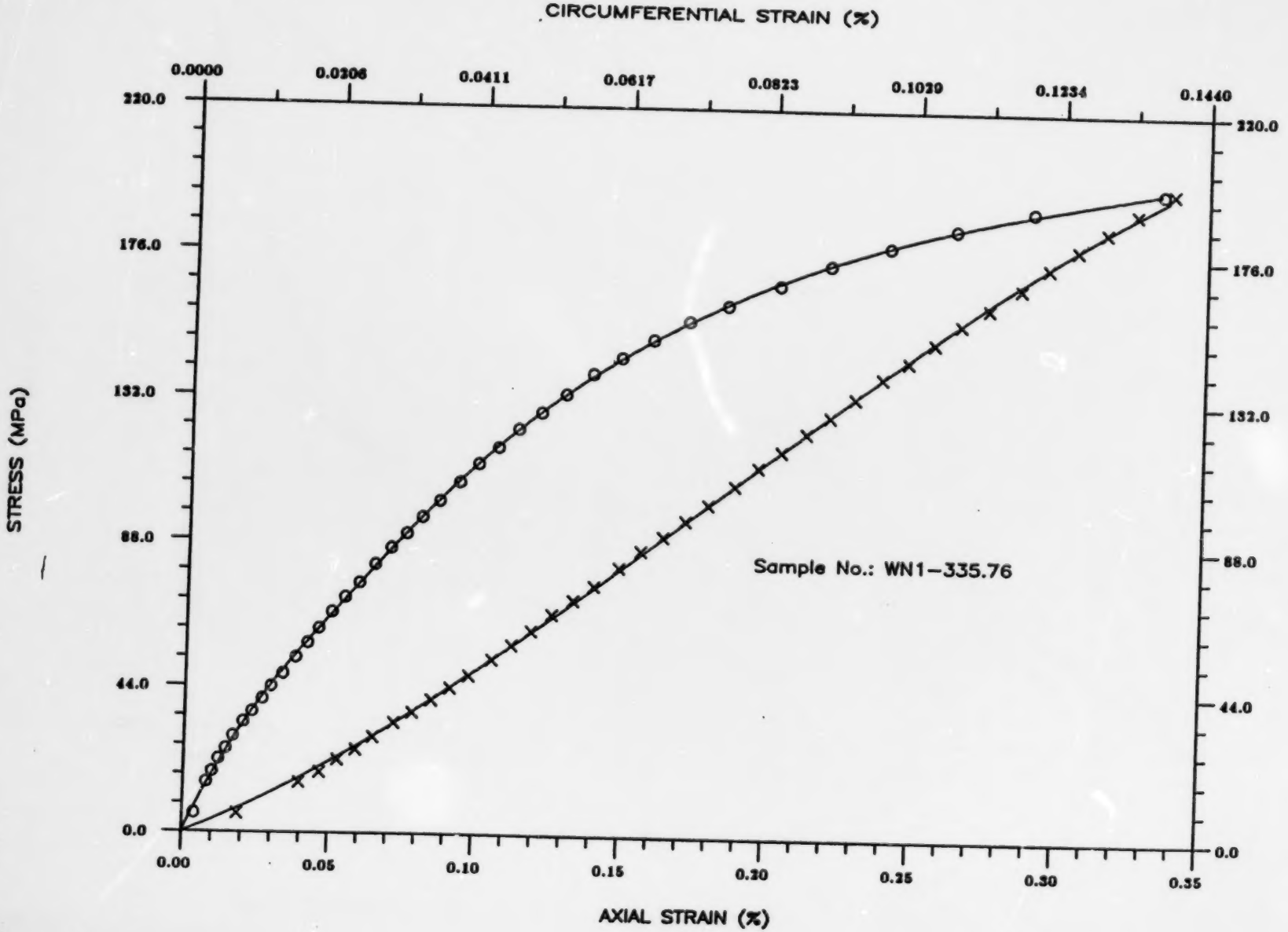

Fig. 29: Axial & Circumferential Stress Strain Curves

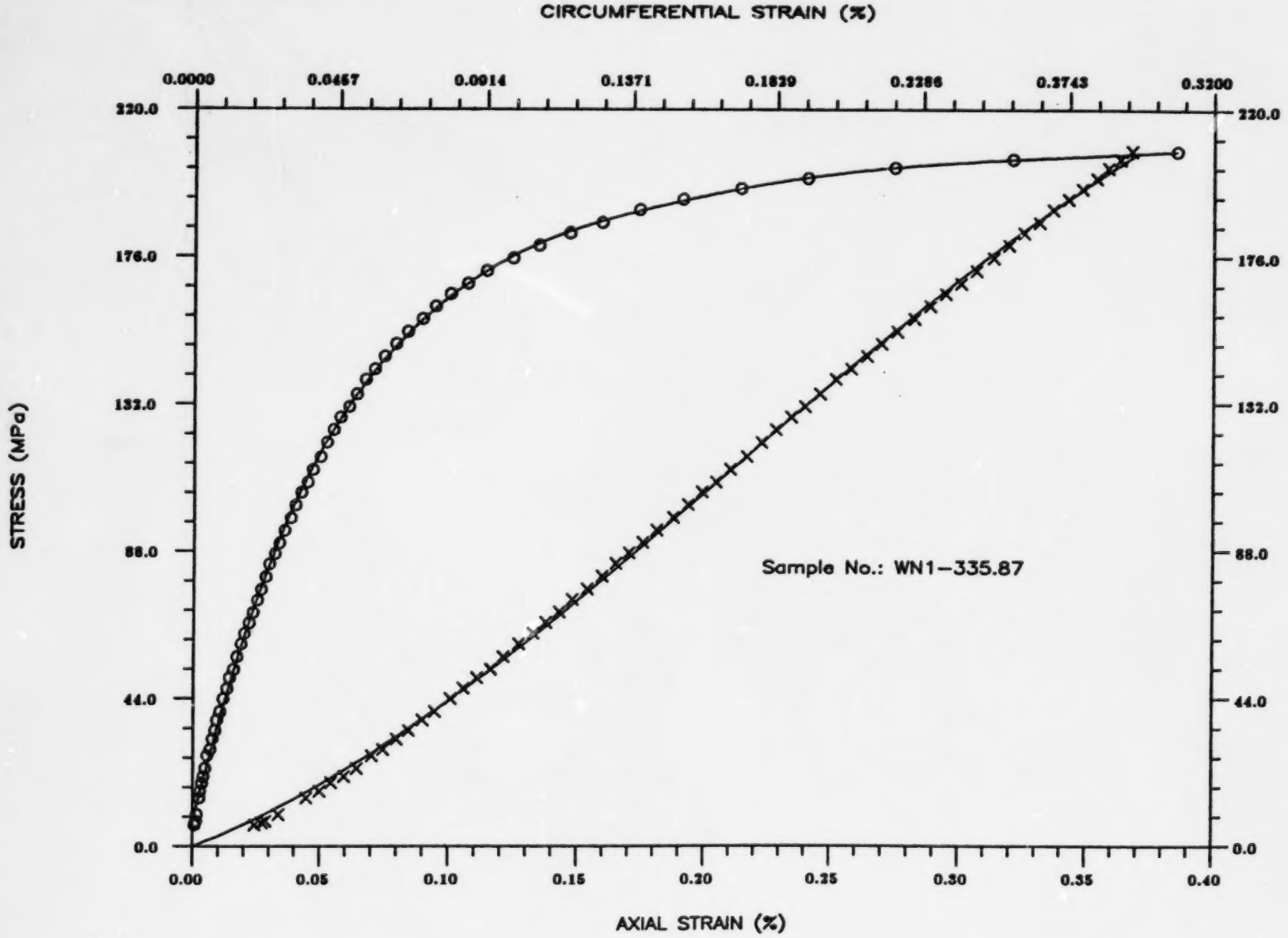

Fig.30:Axial & Circumferential Stress Strain Curves

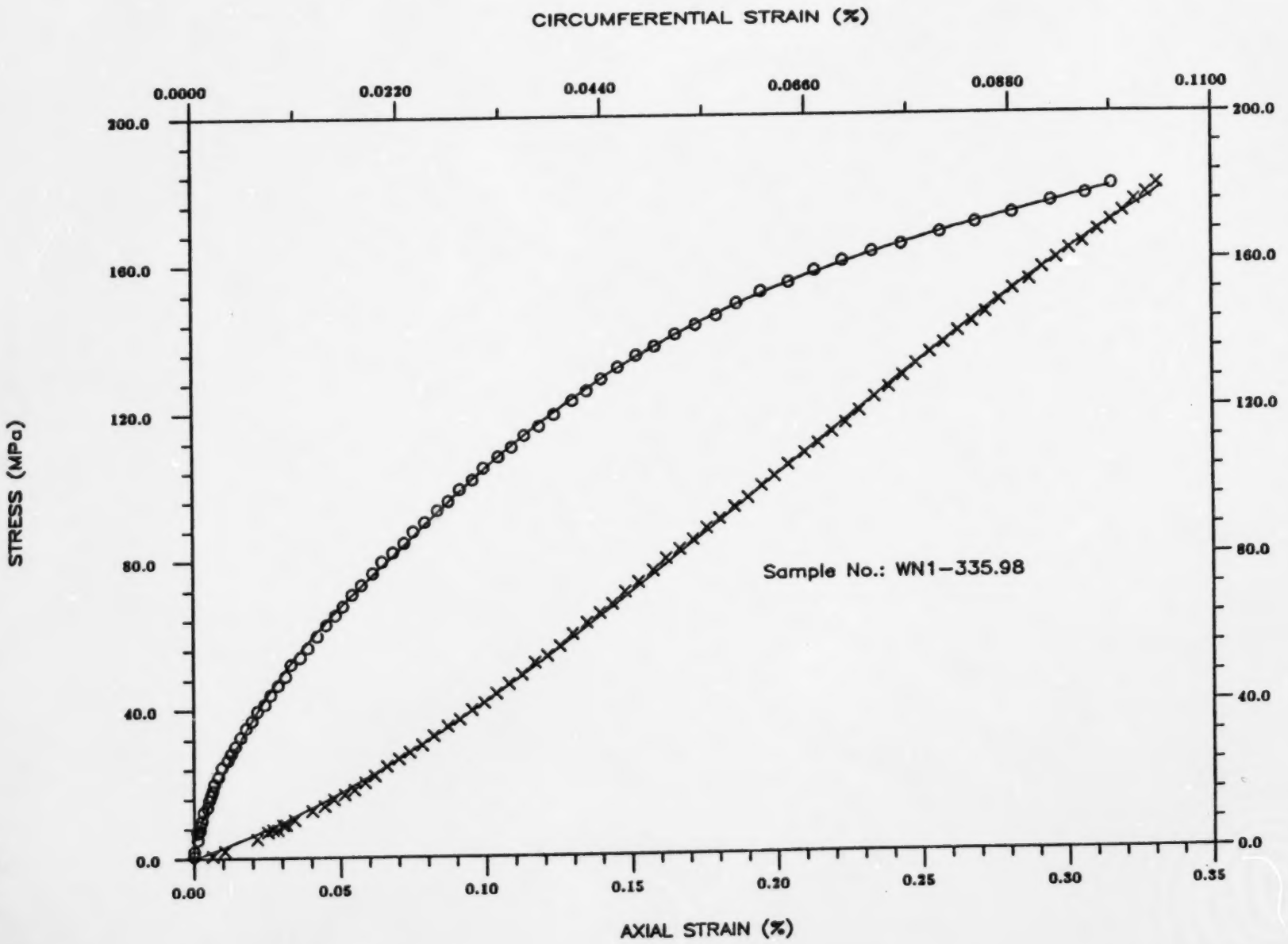

Fig.31 :Axial & Circumferential Stress Strain Curves